Supplementary Blue and Red LED Narrowband Wavelengths Improve Biomass Yield and Nutrient Uptake in Hydroponically Grown Basil

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Abstract. Light emitting diodes (LEDs) can produce a wide range of narrowband wavelengths with varying intensities. Previous studies have demonstrated that supplemental blue (B) and red (R) wavelengths from LEDs impact plant development, physiology, and morphology. High-pressure sodium (HPS) lighting systems are commonly used in greenhouse production, but LEDs have gained popularity in recent years because of their improved energy efficiency and spectral control. Research is needed to determine the efficacy of supplementary B and R LED narrowband wavelengths compared with traditional lighting systems like HPS in terms of yield, quality, and energy consumption for a variety of greenhouse-grown high-value specialty crops. The objective of this study was to determine the impact of LED and HPS lighting on greenhouse hydroponic basil (*Ocimum basilicum* var. ‘Genovese’) biomass production and edible tissue nutrient concentrations across different growing seasons. Basil was chosen because of its high demand and value among restaurants and professional chefs. A total of eight treatments were used: one nonsupplemented natural light (NL) control; one HPS treatment; and six LED treatments (peaked at 447 nm/627 nm, ± 20 nm) with progressive B/R ratios (10B/90R; 20B/80R; 30B/70R; 40B/60R; 50B/50R; and 60B/40R). Each supplemented light (SL) treatment provided $8.64 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ($100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $24 \text{ h}\cdot\text{d}^{-1}$). The daily light integral (DLI) of the NL control averaged $9.5 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ across all growing seasons (ranging from 4 to $18 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$). Relative humidity averaged 50%, with day/night temperatures averaging $27.4^\circ\text{C}/21.8^\circ\text{C}$, respectively. LED treatments had the greatest total fresh biomass (FM) and dry biomass (DM) accumulation; biomass for LED treatments were 1.3 times greater on average than HPS, and 2 times greater than the NL control. Biomass partitioning revealed that the LED treatments had more FM and DM for the individual main stem, shoots, and leaves of each plant at varying levels. LED treatments resulted in greater height and main stem diameter. Some essential nutrient concentrations were impacted by SL treatments and growing season. An energy analysis revealed that on average, narrowband B/R LED treatments were 3 times more energy efficient at increasing biomass over HPS. LED treatments reduced SL energy cost per gram FM increase by 95% to 98% when compared with HPS. In addition, the rate of electricity consumption to biomass increase varied across LED treatments, which demonstrates that basil uses different B/R narrowband ratios at varying efficiencies. This experiment shows that spectral quality of both supplemental sources and natural sunlight impacts primary metabolic resource partitioning of basil. The application of LED lighting systems to supplement natural DLI and spectra during unfavorable growing seasons has the potential to increase overall biomass accumulation and nutrient concentrations in a variety of high-value specialty crops.

competition, and natural geographical layouts. Low sun angles have also been associated with low-red to far-red ratios (Franklin and Whitelam, 2007), while variation in cloud cover is associated with higher blue light levels and lower far-red levels (Smith, 1982). Irradiance and spectral quality are often linked because leaves that are exposed to shade or sun spectra are also exposed to a relatively lower or higher irradiance level (Massa et al., 2008; Morrow, 2008).

Blue (B) and red (R) wavelengths are known to promote primary metabolic reactions such as photosynthesis, while B and high red to far-red (R:FR) ratios induce chloroplast development and alter density (Smith, 1982; Tlalka et al., 1999). Light with insufficient B and R waveband intensities (i.e., irradiance reduction or total absence) can reduce overall yields and photosynthetic rates (Briggs and Huala, 1999; Olle and Virsile, 2013). B/R wavelengths and low R:FR ratios directly impact morphological characteristics such as internode length, leaf size/number/area, node angles, secondary and tertiary branching behaviors, shade avoidance, stomatal function, and so forth (Briggs and Huala, 1999; Christie, 2007; Jensen et al., 2018; Kong et al., 2018; Morrow, 2008; Smith, 1982; Spalholz et al., 2020). In 2019, Kim et al. found that spectral quality impacts biomass allocation in tomato (*Solanum lycopersium* L. ‘Merlice’) plants (Kim et al., 2019). While changes to spectral quality will influence biomass allocation, the impact of discrete narrowband wavelengths on primary metabolic resource partitioning of high-value specialty crops should be further investigated. To understand how light interacts with plants at a fundamental level, it is pertinent to determine the overall metabolic impacts of various discrete narrowband wavelengths along with potential synergistic and antagonistic interactions in broad spectrum lighting.

Supplemental lighting (SL) systems play a vital role in plant research and greenhouse production. Research on spectral responses of various plant species has been limited in the past by technology and the inability to accurately provide narrowband wavelengths (Mitchell et al., 2015). Before the advent of LEDs, special filters were used to alter the spectral quality of broad-spectrum growth lamps with varied success. LEDs provide researchers the opportunity to determine how light quality fundamentally impacts plant growth and development (Massa et al., 2008). In addition, the use of LEDs in horticultural industry has dramatically increased due to continued technological advancements, increased spectral control, improved energy efficiency, and reduction in manufacturing costs (Bantis et al., 2016; Hogewoning et al., 2010; Massa et al., 2008; Singh et al., 2015). LED and high-pressure sodium (HPS) lamps offer many advantages over one another, and a full-scope efficacy comparison is needed to determine the impacts of LED lights over traditional lighting systems. This includes evaluating intensity and spectral regimes to

Light intensity and spectral quality directly impact growth and development characteristics of many plant species. Various primary and secondary metabolic responses occur as light intensity and spectral quality change, such as photosynthesis, photomorphogenesis, and phototropism (Ouzounis et al., 2015). Plants have evolved under broadband spectra and are commonly exposed to spectral variation in nature across changing weather conditions, day length, time of day, and season (Smith, 1982). Altitude impacts spectral quality and light intensity, in addition to neighboring vegetation,

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further optimize greenhouse lighting efficiency (Weaver et al., 2019).

As the technology behind LED SL systems continues to advance, commercial growers will benefit from research focused on determining the efficacy of various SL systems and which type is optimal for generalized greenhouse and controlled environment crop production (Graamans et al., 2018; Singh et al., 2015). Many factors must be considered to make an informed SL purchase, such as energy consumption, energy transformation efficiency, maintenance/bulb lifespan, purchase and operational costs, net profit, intended reasons for supplementation, and individual crop requirements. While some of these factors have been well documented, it would be beneficial to explore the many variables in terms of energy input and subsequent yield and quality output.

One potential use for narrowband LED SL systems is large-scale greenhouse production of high-value specialty crops. The demand for fresh culinary herbs has grown tremendously over the past few decades. Culinary herbs are defined as herbaceous aromatic plants that are grown and sold either fresh (cut herbs, potted plants, pastes, etc.) or dried and packaged (Charles and Simon, 1990). Manufacturers, commercial kitchens, restaurants, and even high-end grocery stores desire high-quality and fresh ingredients to meet this consumer demand, rather than relying on inferior dried products or extracts (Succop and Newman, 2004). Sweet basil (*Ocimum basilicum* var. 'Genovese') is a specific high-value culinary herb that stands out in terms of consumer demand. Greenhouse operations growing this valuable crop have excellent potential for sustainable growth, expansion, and profitability, especially in fresh and high-quality niche markets (Raimondi et al., 2006; Rakocy et al., 2004; Treadwell et al., 2007, 2011).

Large-scale commercial greenhouses are inclined to produce year-round to minimize downtime and maintain competitiveness in the marketplace during unfavorable growing seasons. In general, demand for fresh crops (i.e., basil) will increase during winter months as outdoor productions are forced to pause operations due to cooler temperatures

and the reduction in sunlight (i.e., low supply). Supply is higher during summer months, and staying established year-round can provide a marketplace advantage over outdoor producers. In higher latitude locations, SL may be required to produce quality greenhouse crops during winter months through the management of lighting schedules and photoperiod. In certain situations, increasing the daily light integral (DLI) and optimizing the spectral quality has the potential to improve biomass production and shorten growth cycles (Gouvea et al., 2012; Mitchell et al., 2015; Samuolienė et al., 2012). LED lighting systems have the potential to replace traditional lighting systems in a wide range of horticultural applications and may help growers reduce energy costs while maintaining/improving quality throughout all growing seasons. Current research suggests that providing optimized ratios of B/R wavelengths have a positive impact on primary and secondary metabolism, net biomass yield, and nutritional content in basil as well as other specialty crops and high-value herbs (Bantis et al., 2018; Chen and Yang, 2018; Colquhoun et al., 2013; Kopsell and Sams, 2013; Kopsell et al., 2014; Kopsell et al., 2015, 2017; Metallo et al., 2018; Pennisi et al., 2019; Weaver et al., 2019; Wink, 2010). Many studies have looked at the impacts of LEDs on crop growth and biomass, but it remains unclear how progressive ratios of narrowband dichromatic supplements compare with HPS supplements in terms of yield, seasonal variation, and energy efficiency. For these reasons, it is advantageous to explore the physiological impacts of narrowband B/R LED lighting and determine how manipulating spectral quality can be used to optimize yield and energy efficiency.

The primary objective of this project was to determine the impact of specific narrowband (± 20 nm) blue/red wavelength ratios (peaked at 447 nm/627 nm, respectively) from solid-state LED lighting systems on biomass production and nutrient concentrations in greenhouse hydroponic basil (*Ocimum basilicum* var. 'Genovese'). Unlike previous studies, this project places emphasis on determining the optimal narrowband B/R ratio compared with HPS lighting under greenhouse conditions, the impact of sea-

son's spectral quality and DLI on biomass accumulation in conjunction with SL lighting, and SL energy consumption vs. edible biomass production.

Materials and Methods

Cultural techniques and environmental growing conditions. This project was conducted at the University of Tennessee Institute of Agriculture (UTIA) in Knoxville, TN (lat. 35°56'44.5" N, long. 83°56'17.3" W). Growing dates for six separate experimental cycles occurred from Aug. 2015 to June 2016 and have been labeled as growing seasons. In the greenhouse, 'Genovese' basil seeds (Johnny's Select Seeds, Winslow, ME) were germinated in peatmoss-based cubes (Park's Bio Dome Sponges, Hodges, SC) at 28.3 °C and 95% RH. The 'Genovese' variety of sweet basil was specifically chosen because of its unique flavor profile, high market demand, and preference among professional chefs. After 2 weeks, seedlings were transplanted into 5- × 5-cm plastic pots using 1 part peatmoss (Black Gold Canadian Sphagnum Peat Moss, Agawam, MA) to 3 parts perlite (Krum Horticultural Perlite, Hodgkins, IL) potting mix. Relative humidity during the growth period averaged 55%. Across all six growing seasons, day temperatures averaged 27.4 °C, while night temperatures averaged 21.8 °C. Daily and nightly temperature averages were taken across one full year (Aug. 2015 to Aug. 2016) to determine capacity of greenhouse heating/cooling systems and averaged 29.4 °C/23.8 °C, respectively. The daily light integral (DLI) of the natural light (NL) control averaged 9.5 mol·m⁻²·d⁻¹ across all growing cycles (ranging from 4 to 18 mol·m⁻²·d⁻¹). Specific growing parameters for each growing season may be found in Table 1.

Basil plants were grown in ebb and flow hydroponic systems and sub-irrigated for 5 min each day with a full strength, modified Hoagland's solution. Nutrient solution elemental concentrations were (ppm): N (207.54), P (50.87), K (298.23), Ca (180.15), Mg (77.10), S (136.45), Fe (3.95), Mn (0.90), Zn (0.40), Mo (0.09), Cu (0.90), and B (0.90). The fertility regime was kept constant across the duration of all seasons. All growth (germination to harvest) occurred in the same greenhouse bay, and total

Table 1. Important environmental parameters across growing cycles. All crops grown under greenhouse conditions at the University of Tennessee Institute of Agriculture (UTIA) in Knoxville, TN (35°56'44.5" N, 83°56'17.3" W).

	September	November	January	March	April	June
Growing period	8/14/15– 9/29/15	10/14/15– 11/19/15	12/16/15– 1/29/16	2/10/16– 3/15/16	3/11/16– 4/28/16	5/16/16– 6/23/16
Average day temp	27.33 °C	26.84 °C	25.83 °C	25.85 °C	26.95 °C	27.84 °C
Average night temp	23.61 °C	20.62 °C	19.11 °C	21.01 °C	21.94 °C	22.56 °C
Average relative humidity (RH)	55%	55%	50%	55%	55%	60%
Average daily light integral (DLI) (mol·m ⁻² ·d ⁻¹)	9.81	3.26	4.65	8.62	11.99	14.55
Average day length (h)	12.98	10.35	9.93	11.65	13.20	14.27
Average natural blue 447 nm (± 10 nm) intensity at noon ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	13.8	12.2	10.3	12.1	13.3	14.5
Average natural red 627 nm (± 10 nm) intensity at noon ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	14.8	13.2	10.8	13.5	14.4	15.6

growth time lasted ≈ 45 d across all six experimental cycles. Like many commercial basil growing operations, harvest occurred as the first signs of change from vegetative to reproductive growth were observed (i.e., 8–10 nodes).

Light emission spectra from natural sunlight and all SL treatments were taken across growing seasons (Figs. 1 and 2) with an Apogee PS-200 Spectroradiometer (Apogee, Logan, UT). The NL control was used to establish baseline growth and development parameters under nonsupplemented conditions, as well as used to determine changes to plant physiology in response to variations in spectral quality/intensity across growing seasons. A total of seven SL treatments were applied immediately after seedling transplant: one HPS treatment, and six LED treatments with progressive B/R ratios [10B/90R; 20B/80R; 30B/70R; 40B/60R; 50B/50R; and 60B/40R (Orbital Technologies, Madison, WI)]. Each SL treatment provided $8.64 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ($100 \text{ }\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $24 \text{ h}\cdot\text{d}^{-1}$). Quality tests were performed to determine how these narrowband wavelengths impacted edible biomass yield vs. energy consumption and changes in tissue nutrient concentrations. Number of leaves and shoots in addition to fresh (FM) and dry (DM) biomasses were recorded to determine morphological impacts of blue/red supplemental lighting.

Tissue nutrient analysis. Tissue samples were analyzed to determine changes in nutrient concentrations caused by variations in spectral quality. Air-dried samples (total plant) were ground to less than 30 mesh. Next, 0.5 g (± 0.01) of ground plant material from each sample were placed into 15-ml sterile plastic centrifuge test tubes. An Ethos 1112 microwave digestion unit (Milestone, Bergamo, Italy) was used to process ground plant material. Samples were microwaved for 30 min at 150°C , then cooled for an additional 30 min. A 9.9 ml of ICP matrix solution (2% nitric acid, 0.5% hydrochloric acid, and 97.5% RO water) was placed into 15-ml sterile test tubes. A disposable 1-ml plastic pipette was used to add 0.1 ml of the acid-digested sample mixture to the 9.9-ml ICP matrix solution. This mixture was then thoroughly shaken to ensure that the acid was uniformly distributed within the matrix. An Agilent 7500 Series Inductively Coupled Plasma Mass Spectrometry Unit (ICP-MS) (Agilent Technologies, Santa Clara, CA) was used to determine the nutrient concentrations for each of the tissue samples (Barickman et al., 2013).

Experimental design and statistical analyses. A randomized complete block design was used for this experiment, and lighting treatments were randomized after each experimental cycle to account for variations in NL intensity and spectral quality across growing seasons in the greenhouse production area. Each experimental unit consisted of two plants to improve statistical power and reduce biological variance. All values are presented on a per-plant basis. Six replicates (two plants each) were analyzed in each

treatment, and the experiment was repeated across six growing seasons (six experimental cycles).

All data sets were analyzed by GLM and Mixed Model Analysis of Variance procedures using the statistical software SAS (version 9.4; SAS Institute, Cary, NC). Design and Analysis macro (DandA.sas; created by Arnold Saxton) was used in addition to Tukey's adjustment, regression analysis, and univariate/normalization procedures. Treatments were separated by least significant difference at $\alpha = 0.05$.

Results and Discussion

Biomass parameters. Total FM was impacted by season ($P \leq 0.0001$; $F = 381.30$), lighting treatment ($P \leq 0.0001$; $F = 34.53$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 9.56$). All LED treatments produced significantly higher total FM than the HPS and NL control (Fig. 3). Total plant FM average across LED treatments was 45 g in comparison with the NL control, which was 24 g. Chlorophyll and carotenoid pigments are highly effective at absorbing light at the

Fig. 1. Natural light spectra in greenhouse averaged across all six growing seasons, ranging from 300 to 875 nm. Values were taken at solar noon with three replicates for full sun and overcast for each experimental run. The daily light integral (DLI) of the NL control averaged $9.5 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ across all growing cycles (ranging from 4 to $18 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$).

Fig. 2. Emission spectra of LED and HPS treatments from 300 nm to 750 nm. All treatments provided exactly $8.64 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ($100 \text{ }\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $24 \text{ h}\cdot\text{d}^{-1}$). Readings were taken at midnight to exclude underlying natural solar spectra. LED treatments provided narrowband progressive blue (B)/red (R) lighting ratios (10B/90R; 20B/80R; 30B/70R; 40B/60R; 50B/50R; 60B/40R; expressed as % total light intensity), while the high pressure sodium (HPS) treatment provided broadband light.

supplementary wavelengths provided by the LED treatments, which explains the dramatic increase in biomass accumulation. DLI was equal for all SL treatments; yet all LED treatments had significantly higher yields compared with the HPS treatment, suggesting that spectral quality of SL directly impacts total FM. HPS lighting treatment separated from the NL control for total FM. Most recent papers suggest the use of 640 nm (Darko et al., 2014; Lefsrud et al., 2006, 2008; Samuolienė et al., 2009, 2012, 2013) or 660 nm (Chen and Yang, 2018; Garcia-Caparrós et al., 2018; Li and Kubota, 2009; Lin et al., 2013; Olle and Virsile, 2013; Singh et al., 2015; Stagnari et al., 2018) for the cultivation of common greenhouse crops. Red light has been shown to not have significant increases in biomass across these studies, but B and R combinations of SL showed increased biomass yields and photosynthetic rates (Christie, 2007; Hogewoning et al., 2010; Smith, 1982). In addition, there were some significant changes in biomass across the progressive B/R ratios, which indicates that basil uses these different wavelengths at varying efficiencies for primary metabolism. In growth chambers, one study found that a ratio of B:R of 1:3 had the greatest basil yield (edible FM) when compared with other sole-source supplements (Pennisi et al., 2019), which complement the results of this study when considering blended spectrum of both the optimal LED treatments (10B–40B) and sunlight. The primary difference is that this experiment was conducted under greenhouse conditions replicating commercial production, which includes the changing solar spectrum in addition to the dichromatic supplements. The impact of the natural solar spectrum is also compared across seasons. Both studies indicate biomass optimization within a specific range of B/R ratios and demonstrate that spectral quality has a direct impact on edible biomass production of basil.

Leaf, shoot, and main stem FM followed similar patterns, but showed various impacts to primary metabolic resource partitioning and morphology (Fig. 3). Leaf FM was impacted by season ($P \leq 0.0001$; $F = 316.21$), lighting treatment ($P \leq 0.0001$; $F = 25.35$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 6.28$). LED treatment means for leaf FM did not separate, but all LED treatments were significantly higher than the HPS and NL control (Fig. 3). Edible biomass (leaf FM) for the treatment 40B/60R was 30.9 g per plant as compared with the NL control, which was 15.5 g per plant.

Shoot FM was impacted by season ($P \leq 0.0001$; $F = 205.03$), lighting treatment ($P \leq 0.0001$; $F = 31.92$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 12.64$). HPS and NL shoot weights were significantly lower than all LED treatments (Fig. 3). The 40B/60R treatment yielded 8 g of side shoots per plant, compared with the NL control, which averaged 2.5 g per plant. Exposure to only R light or light with low levels of B can result in stem/shoot elongation and reduction of total biomass, as shown with some com-

Fig. 3. Influence of greenhouse lighting treatments on fresh mass (FM) partitioning (grams per plant) of hydroponically grown ‘Genovese’ basil (*Ocimum basilicum* var. ‘Genovese’) over six consecutive seasons. Six LED treatments with progressive blue (B)/red (R) ratios (10B/90R; 20B/80R; 30B/70R; 40B/60R; 50B/50R; 60B/40R; expressed as % total light intensity), and the high pressure sodium (HPS) treatment provided supplemental light at $8.64 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ($100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $24 \text{ h}\cdot\text{d}^{-1}$). Fresh leaf, shoot, and main stem weight were evaluated separately across light treatments using Tukey’s protected least significant difference, and data for each followed by the same letter are not significantly different ($\alpha = 0.05$). Columns represent total fresh mass per light treatment and columns with the same letter below them are not significantly different ($\alpha = 0.05$).

mon greenhouse crops (Christie, 2007; Hogewoning et al., 2010; Li and Kubota, 2009; Lin et al., 2013; Samuolienė et al., 2012; Smith, 1982). In addition, B wavelengths (in addition to R) are necessary for leaf expansion and have been shown improve biomass production (Li and Kubota, 2009; Lin et al., 2013; Samuolienė et al., 2012). Increasing both the mass, number, and length of secondary/tertiary shoots provides support for the plant to develop edible tissue more rapidly and increases the number of shoot leaves.

Main stem FM was impacted by season ($P \leq 0.0001$; $F = 362.70$), lighting treatment ($P \leq 0.0001$; $F = 28.73$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 9.12$). LED treatments showed significant increases in main stem FM (Fig. 3). LED treatments (11.9 g per plant average) showed a significant increase over the NL control (6.3 g per plant). While increasing the mass of the main stem diverts some primary metabolic products from edible tissue, it provides support for additional shoot and leaf growth. In general, treatments with higher leaf and shoot FM also showed significant increases to main stem FM; the additional metabolic products that diverted to the main stem has a net benefit to overall plant growth and increases the total FM (Fig. 3). Impacts on FM show that light quality can greatly influence growth and edible biomass of greenhouse-grown basil. Lack of yield in the NL control is most likely a consequence of insufficient DLI (intensity changes across seasons) and lack of specific wavelengths (i.e., B and R) necessary for optimal production of primary metabolites.

Total plant DM was impacted by season ($P \leq 0.0001$; $F = 241.11$), lighting treatment

($P \leq 0.0001$; $F = 25.96$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 7.14$). Total plant DM showed a similar pattern as total FM across treatments and seasons. Findings showed 40B/60R produced 4.9 g per plant, which was significantly higher than the total DM for the NL control (2.2 g per plant). Total FM for all LED treatments was significantly higher than the HPS or control (Fig. 4). June showed the highest total plant DM accumulation, almost 6 times higher than the November growing season. June had the highest DLI of any growing season, which explains the increased yields over the winter months (Table 1, Fig. 5). April and June were the best seasons for basil yield (DM) in this experiment, 2 to 6 times higher than the winter months (Fig. 5). Recorded ambient greenhouse day and night temperatures were consistent within a few degrees throughout the entire year, which eliminates seasonal temperature variation as a factor for increased biomass (Table 1). Because supplemental lighting spectrum and intensity were kept consistent throughout the year, and natural DLI values correlate with observed total DM increases ($r^2 = 0.72$; $P \leq 0.0411$; $F = 3.11$), we conclude that seasonal variation in NL intensity is a primary factor for biomass changes across growing seasons.

DM partitioning revealed that leaf, side shoot, and main stem DM were all significantly impacted by lighting treatment (Fig. 4) and season (Fig. 5). In addition, percentages of total weight (leaf, side shoot, and main stem) were significantly impacted across treatments (Fig. 6).

Leaf DM was impacted by season ($P \leq 0.0001$; $F = 245.08$), lighting treatment ($P \leq 0.0001$; $F = 25.79$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 6.53$). The treatment 40B/60R was ≈ 1.5 g per plant higher than the NL control (Fig. 4). High levels of B wavelengths (i.e., 60B/40R treatment) slightly reduced leaf DM. Intensity was consistent across LED treatments, further demonstrating the impact of spectral quality on primary metabolic resource partitioning. June showed the highest leaf DM accumulation in comparison with other growing seasons. Winter seasons experienced a 3 times decrease in comparison with the optimal June growing season, and the winter months did not separate (Fig. 5). The percentage of DM allocated to leaf tissue in 30B/70R was significantly higher than the HPS, 60B/40R treatment, and NL control. The high B treatment (60B/40R) showed $\approx 30\%$ decrease in leaf DM when compared with the 30B/70R and 40B/60R treatments. (Fig. 6).

Shoot DM was impacted by season ($P \leq 0.0001$; $F = 73.30$), lighting treatment ($P \leq 0.0001$; $F = 14.12$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 4.70$). LED lighting treatments, HPS, and NL control had mixed separation (Fig. 4). June and April were the best growing seasons, with 10 times shoot DM increases over the September growing season (Fig. 5). The percentage of DM allocated to shoot tissue in 40B/60R was significantly higher than the HPS, 60B/40R treatment, 20B/80R treatment, and NL control (Fig. 6).

Main stem DM was also impacted by season ($P \leq 0.0001$; $F = 215.31$), lighting treatment ($P \leq 0.0001$; $F = 17.74$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 6.15$). LED treatments did not separate well except 40B/60R and 60B/40R; most LED treatments showed significance over the HPS and NL control (Fig. 4). April and June showed the highest main stem DM accumulation, with about 6 times increase over the September growing season (Fig. 5). The percentage of DM allocated to main stem tissue was highest in the NL control and HPS, which was significantly higher than all the LED treatments (Fig. 6).

Physical counts and biometrics. Main stem leaf counts were impacted by season ($P \leq 0.0001$; $F = 33.76$), lighting treatment ($P \leq 0.0001$; $F = 5.17$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 6.27$). A few of the LED treatments separated from the NL control and HPS, but many did not (Table 2). Side shoot leaf counts were impacted by season ($P \leq 0.0001$; $F = 96.45$), lighting treatment ($P \leq 0.0001$; $F = 11.16$), and season $\times$ treatment interactions ($P \leq 0.0116$; $F = 2.11$). None of the LED treatments separated, but 40B–50B was significantly higher than the HPS and NL control for both main stem and side shoot leaf counts (Table 2). The LED treatments had the same DLI as the HPS treatment, but all LED treatments had significantly more main stem and side shoot leaves, indicating the spectral

quality has a direct impact on leaf number. In addition, the HPS and NL control had a difference of $8.64 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (across all growing seasons) and did not statistically

separate, which further demonstrates the impact of spectral quality on leaf number.

Plant height was impacted by season ($P \leq 0.0001$; $F = 232.41$), lighting treatment ($P \leq$

Fig. 4. Influence of greenhouse lighting treatments on dry mass (DM) partitioning (grams per plant) of hydroponically grown ‘Genovese’ basil (*Ocimum basilicum* var. ‘Genovese’) over six consecutive seasons. Six LED treatments with progressive blue (B)/red (R) ratios (10B/90R; 20B/80R; 30B/70R; 40B/60R; 50B/50R; 60B/40R; expressed as % total light intensity), and the high pressure sodium (HPS) treatment provided supplemental light at $8.64 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ($100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $24 \text{ h}\cdot\text{d}^{-1}$). Dry leaf, shoot, and main stem weight were evaluated separately across light treatments using Tukey’s protected least significant difference, and data for each followed by the same letter are not significantly different ($\alpha = 0.05$). Columns represent total dry mass per light treatment and columns with the same letter below them are not significantly different ($\alpha = 0.05$).

Fig. 5. Influence of season on DM weight distribution of hydroponically grown ‘Genovese’ basil (*Ocimum basilicum* var. ‘Genovese’). Average of six LED treatments with progressive blue (B)/red (R) ratios (10B/90R; 20B/80R; 30B/70R; 40B/60R; 50B/50R; 60B/40R; expressed as % total light intensity), and the high pressure sodium (HPS) treatment provided supplemental light at $8.64 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ($100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $24 \text{ h}\cdot\text{d}^{-1}$). Dry leaf, shoot, and main stem weight were evaluated separately across growing seasons using Tukey’s protected least significant difference, and data for each followed by the same letter are not significantly different ($\alpha = 0.05$). Columns represent total dry mass per growing season and columns with the same letter below them are not significantly different ($\alpha = 0.05$).

Fig. 6. Influence of greenhouse lighting treatments on dry mass (DM) distribution percentage (primary metabolic resource partitioning) of hydroponically grown 'Genovese' basil (*Ocimum basilicum* var. 'Genovese') over six consecutive seasons. Six LED treatments with progressive blue (B)/red (R) ratios (10B/90R; 20B/80R; 30B/70R; 40B/60R; 50B/50R; 60B/40R; expressed as % total light intensity), and the high pressure sodium (HPS) treatment provided supplemental light at $8.64 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ($100 \text{ }\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $24 \text{ h}\cdot\text{d}^{-1}$). Dry leaf, shoot, and main stem weight were evaluated separately across light treatments using Tukey's protected least significant difference, and data for each followed by the same letter are not significantly different ($\alpha = 0.05$).

Fig. 7. Visual representation of LED lighting impacts on morphology of hydroponically grown 'Genovese' basil (*Ocimum basilicum* var. 'Genovese'). Photo taken directly before June harvest and shows comparison of variations in height, canopy size, leaf area, and pigmentation after being exposed to supplemental blue/red LED ratios, natural light (NL) control, and broad-spectrum HPS supplemental lighting. All treatments (except NL control) were provided $100 \text{ }\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of supplemental light from transplant to harvest.

0.0001; $F = 46.13$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 4.97$). LED lighting treatments showed increased heights over the NL control and HPS, demonstrating that spectral quality impacts plant height (Table 2, Fig. 7). Plants from the NL control and HPS treatment were significantly shorter than plants treated with LED lights, which is consistent with a basil study conducted by Carvalho et al. (2016). Again, the HPS and NL control had a difference of $8.64 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ and did not statistically separate. This further proves that spectral quality has a direct impact on plant height.

Stem diameter (at ground level) was significantly impacted by season ($P \leq 0.0001$; $F = 434.39$), lighting treatment ($P \leq 0.0001$; $F = 58.79$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 7.24$). The NL control and HPS

treatment had significantly smaller stem diameters than the 20B–50B treatments (Table 2).

Macronutrient concentrations. Lighting treatments primarily impacted macronutrient tissue concentrations. Growing season showed some effect on macronutrient concentrations as well. Tissue phosphorous (P) was impacted by season ($P \leq 0.0001$; $F = 56.92$), lighting treatment ($P = 0.0044$; $F = 2.88$), and season $\times$ treatment interactions ($P = 0.0006$; $F = 2.06$). The 20B/80R treatment and the NL control showed separation; however, the rest of the treatments did not separate (Table 3). Kopsell and Sams (2013) showed similar results when analyzing nutrient uptake in sprouting broccoli microgreen shoot tissues (*Brassica oleracea* var. *italica*), in which B light resulted in higher accumulation of K, Ca, Mg, and P. The NL control

only statistically separated from the 20B/80R treatment. Spring seasons accumulated the most P compared with fall and winter growing seasons (Table 4).

Tissue potassium (K) was impacted by season ($P \leq 0.0001$; $F = 8.54$) and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 3.07$), but not by lighting treatment ($P = 0.3931$; $F = 1.06$). There were no statistically significant K impacts observed among lighting treatments (Table 3). Plants grown in fall and early winter months had significantly higher K concentrations, while spring seasons had varying K concentrations (Table 4).

Tissue calcium (Ca) was impacted by season ($P \leq 0.0001$; $F = 83.20$), lighting treatment ($P \leq 0.0001$; $F = 4.60$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 3.38$). There were slightly elevated levels of Ca in 10B/90R and 50B/50R treatments as compared with the NL control, but many LED treatments did not separate (Table 3). January had the highest Ca tissue concentrations, while March had the lowest (Table 4). A study on lettuce suggested that blue light would increase K and Ca, while mixtures of B and R would increase Fe, P, and Mg (Amoozgar et al., 2017).

Tissue sulfur (S) was impacted by season ($P \leq 0.0001$; $F = 17.09$) and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 2.33$), but not by lighting treatment ($P = 0.0009$; $F = 3.43$). There were no statistically significant S impacts observed among lighting treatments, except the NL control and high B treatments (Table 3). Plants grown in the fall and early winter months had significantly higher S concentrations, while spring seasons had varying S concentrations (Table 4).

Tissue magnesium (Mg) was impacted by season ($P \leq 0.0001$; $F = 6.41$), lighting treatment ($P \leq 0.0001$; $F = 4.21$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 3.43$). Mg concentrations in some LED treatments showed significant separation from the HPS and NL control (Table 3). March was the only season that separated from the others (Table 4).

Micronutrient concentrations. Tissue boron (B) was impacted by season ($P \leq 0.0001$; $F = 83.49$), lighting treatment ($P \leq 0.0001$; $F = 8.62$), and season $\times$ treatment interactions ($P \leq 0.0001$; $F = 2.60$). It was the only micronutrient to have separation across lighting treatments. The 50B/50R LED treatment had tissue B concentrations of $66.7 \text{ }\mu\text{g}\cdot\text{g}^{-1}$ DM, with many of the LED treatments within $5 \text{ }\mu\text{g}\cdot\text{g}^{-1}$ DM of this treatment. The NL control and HPS treatments were significantly lower than the top LED treatments. Boron is primarily used for cell division and cell wall synthesis, and sub-optimal levels of B are known to reduce uptake of P and K levels. Previous studies from our group (Kopsell and Sams, 2013; Kopsell et al., 2014, 2015, 2017) showed that overall nutrient concentrations increased under supplemental B/R wavelengths. Plants grown in January had significantly higher B

Table 2. Influence of greenhouse lighting treatments on physical counts and biometrics of hydroponically grown ‘Genovese’ basil (*Ocimum basilicum* var. ‘Genovese’) over six consecutive seasons.^z

Physical counts			
Light treatment	Shoot number	Side shoot leaf number	Main stem leaf number
LED (10B/90R)	33 a	101 abcd	29 abc
LED (20B/80R)	28 ab	96 bcd	31 abc
LED (30B/70R)	35 a	111 abc	32 ab
LED (40B/60R)	34 a	115 ab	34 a
LED (50B/50R)	31 ab	118 a	35 a
LED (60B/40R)	32 a	104 abcd	30 abc
NL control	21 bc	80 cd	26 bc
HPS	24 bc	84 cd	20 c
Biometrics			
Light treatment	Avg plant ht (cm)	Avg stem diam (mm)	
LED (10B/90R)	26.1 bc	3.5 bc	
LED (20B/80R)	28.3 abc	3.9 a	
LED (30B/70R)	27.2 bc	3.6 ab	
LED (40B/60R)	29.7 ab	3.9 a	
LED (50B/50R)	26.9 bc	3.7 ab	
LED (60B/40R)	26.1 c	3.3 c	
NL control	19.5 d	2.7 d	
HPS	19.1 d	3.3 c	

^zMean values represent the average of two plants per replication (experimental unit) and six replications per treatment. Values were analyzed using Tukey’s protected least significant difference, and data in the same column followed by the same letter are not significantly different ($\alpha = 0.05$).

Table 3. Influence of LED treatments on tissue mineral concentrations of hydroponically grown ‘Genovese’ basil (*Ocimum basilicum* var. ‘Genovese’). The daily light integral (DLI) of the NL control averaged 9.5 mol·m⁻²·d⁻¹ during the growth period (ranging from 4 to 18 mol·m⁻²·d⁻¹).^z

Macronutrients							
Light treatment	P	K	Ca	S	Mg		
LED (10B/90R)	11,810 ab	73,810 a	13,780 a	5,088 ab	7,885 ab		
LED (20B/80R)	11,930 a	72,200 a	13,180 ab	4,945 ab	7,511 abc		
LED (30B/70R)	11,300 ab	68,450 a	12,760 abc	4,917 ab	7,258 abc		
LED (40B/60R)	11,670 ab	73,790 a	13,010 abc	5,211 a	7,773 ab		
LED (50B/50R)	11,450 ab	73,950 a	13,510 a	5,212 a	8,092 a		
LED (60B/40R)	11,720 ab	73,910 a	13,010 abc	5,143 a	7,680 abc		
NL control	10,240 b	72,670 a	11,270 c	4,493 b	6,723 c		
HPS	10,780 ab	75,740 a	11,940 abc	4,660 ab	6,964 bc		
Micronutrients							
Light treatment	B	Cu	Mn	Fe	Na	Zn	Mo
LED (10B/90R)	63.21 ab	32.61 a	158.2 a	167.2 a	594.3 a	73.13 a	0.32 a
LED (20B/80R)	62.53 ab	19.81 a	146.1 a	154.7 a	530.6 a	64.04 a	0.36 a
LED (30B/70R)	57.09 bcd	25.17 a	155.1 a	165.9 a	530.1 a	67.33 a	0.34 a
LED (40B/60R)	65.76 ab	20.52 a	157.4 a	154.3 a	516.1 a	67.81 a	0.40 a
LED (50B/50R)	66.67 a	25.69 a	158.1 a	161.7 a	565.8 a	73.55 a	0.38 a
LED (60B/40R)	62.19 abc	18.34 a	155.8 a	164.3 a	490.5 a	66.36 a	0.43 a
NL control	49.44 d	21.12 a	155.3 a	150.8 a	558.2 a	63.29 a	0.46 a
HPS	52.77 cd	17.06 a	150.9 a	151.3 a	573.9 a	66.75 a	0.43 a

^zAll concentrations are presented in micrograms per gram dry plant weight (µg·g⁻¹ DM). LED treatments provided narrowband blue (B)/red (R) wavelengths (447 nm/627 nm). Mean values represent two plants per replication and six replications per treatment. Values are averaged across all six growing seasons. Values were analyzed using Tukey’s protected least significant difference, and data in the same column followed by the same letter are not significantly different ($\alpha = 0.05$).

concentrations in comparison with all other seasons (Table 4).

Tissue copper (Cu) was impacted by season ($P = 0.0021$; $F = 5.04$), but not by season × treatment interactions ($P = 0.8356$; $F = 0.77$) or lighting treatment ($P = 0.2791$; $F = 1.23$). There were no statistically significant Cu impacts observed among lighting treatments (Table 3). Significance was varied across winter and spring months (Table 4).

Tissue manganese (Mn) was impacted by season ($P \leq 0.0001$; $F = 6.05$) and season × treatment interactions ($P = 0.0002$; $F = 2.15$), but not by lighting treatment ($P = 0.7407$; $F = 0.64$). There were no statistically significant Mn impacts observed among lighting treatments (Table 3). Plants grown in early fall and spring months had significantly higher Mn concentrations, while January showed the lowest levels (Table 4).

Tissue iron (Fe) was impacted by season ($P \leq 0.0001$; $F = 11.17$), but not by season × treatment interactions ($P = 0.1953$; $F = 1.21$) or lighting treatment ($P = 0.8490$; $F = 0.51$). There were no statistically significant Fe concentration impacts observed among lighting treatments (Table 3). Plants grown in the early fall and spring months had significantly higher Fe concentrations, while the winter seasons had varying Fe concentrations (Table 4).

Tissue sodium (Na) was impacted by season ($P \leq 0.0001$; $F = 78.74$) and season × treatment interactions ($P \leq 0.0001$; $F = 3.65$), but not by lighting treatment ($P = 0.3168$; $F = 1.17$). There were no statistically significant Na impacts observed among lighting treatments (Table 3). Plants grown in the fall and early winter months had significantly higher Na concentrations, while the

spring seasons had varying Na concentrations (Table 4).

Tissue zinc (Zn) was impacted by season ($P \leq 0.0001$; $F = 24.38$), but not by season × treatment interactions ($P = 0.1449$; $F = 1.26$) or lighting treatment ($P = 0.4999$; $F = 0.92$). There were no statistically significant Zn impacts observed among lighting treatments (Table 3). Plants grown in early the fall and spring months had significantly higher Zn concentrations, while the winter seasons in general had lower Zn concentrations (Table 4).

Tissue molybdenum (Mo) was impacted by season ($P \leq 0.0001$; $F = 416.44$), but not by season × treatment interactions ($P = 0.9899$; $F = 0.34$) or lighting treatment ($P = 0.3293$; $F = 1.15$). There were no statistically significant Mo impacts observed among lighting treatments (Table 3). Plants grown

Table 4. Influence of growing season on tissue mineral concentrations of hydroponically grown ‘Genovese’ basil (*Ocimum basilicum* var. ‘Genovese’).^z

Macronutrients							
Growing season	P	K	Ca	S	Mg		
September	10,140 b	73,150 ab	10,710 d	5,407 a	7,640 a		
November	10,846 b	76,830 a	13,090 c	4,425 a	7,534 a		
January	8,147 c	77,890 a	15,580 a	4,385 c	7,273 ab		
March	10,320 b	75,190 ab	7,461 e	5,173 ab	6,559 b		
April	13,610 a	68,620 bc	13,890 bc	4,836 bc	7,691 a		
June	14,440 a	65,430 c	15,280 ab	4,362 c	7,914 a		
Micronutrients							
Growing season	B	Cu	Mn	Fe	Na	Zn	Mo
September	57.82 b	33.29 a	158.2 ab	183.2 ab	696.3 a	76.23 ab	0.10 c
November	38.36 d	11.75 b	147.1 bc	128.1 c	710.6 a	52.22 c	0.13 c
January	83.84 a	20.22 ab	140.1 c	152.9 bc	761.2 a	68.43 b	1.42 b
March	64.42 b	19.71 ab	151.4 abc	125.6 c	502.6 b	46.51 c	1.57 a
April	46.40 c	21.55 ab	164.1 a	162.4 ab	221.1 d	82.55 a	1.42 b
June	64.33 b	28.93 a	165.8 a	193.9 a	363.9 c	83.22 a	1.55 ab

^zAll concentrations are presented in micrograms per gram dry plant weight ($\mu\text{g}\cdot\text{g}^{-1}$ DM). Mean values represent two plants per replication and six replications per treatment. Values for each season are averaged across all treatments within that season. Values were analyzed using Tukey’s protected least significant difference, and data in the same column followed by the same letter are not significantly different ($\alpha = 0.05$).

Table 5. Efficacy comparison of supplementary lighting (SL) on hydroponically grown ‘Genovese’ basil (*Ocimum basilicum* var. ‘Genovese’) in terms of energy consumption and biomass increase.

Light treatment	SL energy input (watts)	SL total energy input per harvest cycle (kWh)	SL energy total cost (U.S. dollars) ^y	Yield (g) ^z	Yield increase over NL control (g) ^z	SL energy input per yield increase (kWh/g) ^z	Total yield increase per SL energy cost (g/U.S. dollars) ^y
LED (10B/90R)	150	162	12.96	46	22	7.36	1.69
LED (20B/80R)	150	162	12.96	45	21	7.71	1.62
LED (30B/70R)	150	162	12.96	47	23	7.04	1.77
LED (40B/60R)	150	162	12.96	49	25	6.48	1.93
LED (50B/50R)	150	162	12.96	42	18	9.00	1.39
LED (60B/40R)	150	162	12.96	40	16	10.13	1.23
HPS	1000	1080	86.40	29	5	32.4	0.06
NL control	0	0	0	24	0	–	–

^zGrams per plant basis, average across six growing seasons.

^yElectricity assumed \$0.08 per kWh.

in June had the highest Mo concentrations, while the fall and winter seasons had significantly lower (10 to 15 times) concentrations (Table 4).

Efficacy of supplemental lighting and energy consumption analysis. Determining the optimal greenhouse SL spectra for common fresh-market high-value specialty crops has the potential to significantly increase edible yield while reducing the consumption of electricity. While SL spectra optimization is important for yield and energy efficiency in greenhouse production, it is even more critical for indoor farms and CEA systems that do not use natural sunlight. In this experiment, all LED treatments surpassed the traditional lighting system (HPS) and the NL control in terms of SL energy input to yield increase (Table 5). On average, LED treatments were able to effectively double the total FM increase per plant, as compared with the HPS lighting system, which only provided a 1.2 times increase over the NL control. Narrowband LEDs provided the crop with the same lighting intensity but consumed 85% less energy on average than the broadband HPS treatment (LEDs used 162 kWh over the 45-d growing period as compared with 1080 kWh used by the HPS treatment). Evaluating the kWh of SL energy input by FM increase per plant beyond the NL control baseline (kWh/g FM increase over NL control) revealed that the LED

treatments on average were 3 times more energy efficient at increasing FM as compared with the HPS (Table 5). In other words, it required 3 times the energy input per gram FM increase when using HPS broadband lighting as compared with B/R narrowband LEDs. Furthermore, comparing the total yield increase (g) per U.S. dollar (\$) spent on SL energy shows that the LED treatments are 95% to 98% more cost effective (assuming the current rate of \$0.08 per kWh). Each dollar spent on energy for SL LED lighting resulted in a 1.23–1.93 g per plant increase, while each dollar spent on HPS lighting only resulted in a 0.06 g per plant increase (Table 5). While there are dramatic differences between the HPS and LED average in terms of FM increase and energy efficiency, significant variation exists among individual LED treatments. The most efficient B/R ratio for FM increase was 40B/60R (Table 5). Because the intensity was equal across all SL treatments, spectral quality must be responsible for the significant FM increases and directly impacted primary metabolism. LED treatments varied from a 6.48 kWh/g FM to 10.13 kWh/g FM, suggesting photosystems I/II and other secondary pigments use these narrowband B/R ratios with varying efficiencies. Optimizing the spectral quality of greenhouse SL lighting, whether that be narrow or broadband supplements, has the potential to decrease

energy consumption while increasing crop yields.

When considering energy efficiency of supplemental lighting, it is also important to consider both ambient temperature and leaf temperatures. It has been well established that one of the major factors that influences yield is temperature, because temperature has a direct impact on key enzyme activities and metabolic rate. HPS lamps emit large amounts of yellow wavebands that are not particularly suited for photosynthesis. In addition, they emit heat energy in the form of infrared (IR) wavelengths that may impact photosynthetic/respiratory rates of crops and therefore impact net biomass accumulation as well as the production of other primary and secondary metabolites. In this experiment, ambient growing temperatures were kept consistent across growing seasons (within 1 to 2 °C), but 2 to 3 °C leaf temperature differences were observed across growing seasons. Care was taken to ensure leaf temperature differences were minimal between treatments. Because HPS lamps produce an extraordinary amount of heat, the fixture was distanced from the crop in order keep leaf temperatures and PPFD similar across all treatments. For commercial growers located in cold environments or who have harsh winter months, traditional lighting sources (HPS) may slightly offset heating costs due to extra radiant heat energy and increased

photosynthetic yield because of the increased leaf temperature or ambient heat produced from the fixture. In the summer, this additional heat energy will likely become problematic and may surpass the quenching ability of accessory pigments (i.e., xanthophyll cycle overload), causing protein denaturation and photooxidative damage. Depending on the operation size and many other factors, this may persuade or dissuade potential LED customers from making a purchase. HPS and other high intensity discharge (HID) traditional lighting sources use vast amounts of electrical energy and convert a large portion of that energy into excess heat/IR wavelengths. In most cases, natural gas and propane are much cheaper than electricity, and both are inherently more efficient at the conversion of energy needed to produce heat (i.e., raise the ambient air temperature). It is possible that heat energy and IR wavelengths directed on the canopy (i.e., an HPS fixture placed closer to the crop canopy) will have other impacts on metabolism, rather than ambient temperature, and may benefit certain parameters that are important for yield or sensory quality. Other wavelengths within the HPS spectrum or white LEDs (broad-range spectral quality with key narrowband wavelengths at specific ratios) may benefit growth. Overall effects on morphology should be considered. For example, increases in leaf area or node angle may prove useful for increasing overall photosynthetic rates, absorption of light energy, temperature flux, and visual appeal to customers. For these reasons, further efficacy comparisons between HPS and LED lighting systems (narrow and broadband) should be conducted to determine impact on yield and various quality parameters. This information can be used to establish economically favorable SL regimes for a variety of high-value specialty crops.

Conclusion

Narrowband B and R LED treatments significantly increased both fresh/dry edible biomass yield and impacted tissue concentrations of some macro and micronutrients when compared with the HPS and the NL control. Biomass for LED treatments were 1.3 times greater on average than HPS, and 2 times greater than the NL control. FM and DM biomass partitioning revealed that the LED treatments influenced primary metabolic resource partitioning. Biometric analysis showed LED treatments resulted greater height, main stem diameter, and leaf/shoot counts. Edible biomass and macro/micronutrient concentrations were also impacted by growing season, which can be attributed to seasonal variations in DLI and spectral quality. An energy analysis revealed that on average, narrowband B and R LED treatments were 3 times more energy efficient at increasing biomass over HPS. LED treatments reduced SL energy cost per gram FM increase by 95% to 98% when compared with HPS. In addition, the ratio of electricity

consumption to biomass increase varied across LED treatments, which demonstrates that basil uses different B and R narrowband ratios at varying efficiencies for photosynthesis. The data from this experiment show that it is more cost effective and energy efficient to use narrowband LEDs with optimized spectral quality to increase biomass as compared with traditional HPS lighting systems.

Considering all parameters in this study, we have concluded that the optimal ratio of B/R is between 20B/80R to 40B/60R. The B/R narrowband wavelengths (447 nm/627 nm) used in this experiment (at 30B/70R) align well with the absorption spectra of chlorophyll a/b as well as the natural solar spectrum (full sun) at solar noon during the late spring to midsummer growing seasons, providing an evolutionary basis for this B/R ratio being optimal for primary metabolism. We have shown that supplementing the natural solar spectrum with these narrowband wavelengths can significantly increase yields and tissue nutrient concentrations. By adding these narrowband B/R wavelengths at this ratio during the winter months when DLI and spectral quality are lacking, growers can substantially yet efficiently increase yield from their crops. Not only were these B/R supplements beneficial during the winter months, but they also provided significant impacts to biomass and tissue nutrient concentrations during the spring–summer growing seasons when DLI and spectral quality were sufficient for quality basil production.

Results from this study support the growing body of literature that detail photomorphogenic responses, biomass increases, and impacts on tissue nutrient concentrations through exposure to specific B and R wavelengths from LED lighting. This experiment demonstrates that the manipulation of spectral quality as well as the addition of specific narrowband wavelengths impact plant morphology and primary metabolic resource partitioning. The application of LED lighting systems to supplement natural DLI and spectra during unfavorable growing seasons has the potential to increase overall biomass accumulation and nutrient concentrations in a variety of high-value specialty crops.

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