THESIS

SUPPLEMENTAL LIGHT-EMITTING DIODE EFFECTS ON THE GROWTH, FRUIT QUALITY, AND YIELD OF TWO GREENHOUSE-GROWN STRAWBERRY (*Fragaria* X *ananassa*) CULTIVARS

Submitted by

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ABSTRACT

SUPPLEMENTAL LIGHT-EMITTING DIODE EFFECTS ON THE GROWTH, FRUIT QUALITY, AND YIELD OF TWO GREENHOUSE-GROWN STRAWBERRY (*Fragaria* X *ananassa*) CULTIVARS

Recent interest in off-season, greenhouse-grown food crops using supplemental top lighting (STL) has created opportunities for controlled environmental agriculture (CEA) production of high-value fruit crops such as strawberries (*Fragaria* X *ananassa*). Light-emitting diodes (LEDs) can be tailored to specific wavelengths to promote increased production and quality of greenhouse-grown crops when used as STL. However, more research is needed to evaluate specific wavelengths of light that can promote increased strawberry fruit production and overall fruit quality in a greenhouse environment. The objectives of this study were to evaluate the effects of three LED STL bars on off-season CEA production of two day-neutral strawberry cultivars, 'Albion' and 'San Andreas'. LED effects on overall vegetative biomass (e.g. stolon production, crown numbers, and leaf area), marketable fruit yield, and fruit quality (e.g. individual fruit weight and soluble solids content (SSC)) were measured during decreasing day lengths of Oct. – Dec. 2017 (Exp. 1) and the increasing day lengths of Jan. – April 2018 (Exp. 2). We hypothesized that the addition of STL via three LED bars would increase most measured parameters. Specifically, it was expected that the LED bars with higher densities of blue and red light would produce higher yields and also increase soluble solids content of the berries. The hypotheses were tested by evaluating three LED light top bars (WFR = white far-red, HB = high blue, and LB = low blue) with peaks of blue (450 nm) and red light (665 nm), but at differing photon flux densities (PFD).

In these experiments, individual strawberry fruit size and SSC were increased with the use of HB and LB LEDs during the shortening days of Exp. 1. Increased leaf area and crown numbers were also positively affected within all LED treatments (WFR, LB, HB) for ‘San Andreas’. The lengthening days of Exp. 2 elicited limited fruiting responses, but stolon production increased within all treatments. In some cases, the two cultivars responded differently to LED STL treatments for leaf area and SSC: ‘San Andreas’ produced larger leaves and ‘Albion’ berries having higher SSC than ‘San Andreas’. Individual fruit weight of both cultivars increased fruit size in LB and HB treatments in both Exp. 1 and Exp. 2. Our studies indicate that the addition of STL, improved overall strawberry fruit quality and plant growth during shortening day lengths in a greenhouse.

ACKNOWLEDGEMENTS

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1.1 Introduction

Due to increasing interest in local produce, the demand for fresh fruits and vegetables will likely increase and create opportunities for the produce industry to grow more food throughout the entire year. Already lucrative fruit crops, such as berries, are even more highly valued when consumers can purchase produce from a local grower or market (Conner et al., 2009). California, Florida, Oregon, and Washington present the largest amount of strawberry (*Fragaria* X *ananassa*) production in the U.S., accounting for 96% of the land area (20,437 ha). California and Florida dominate in production with greater than 90% occurring in the two states (NASS, 2017), yielding a combined 1.20 million metric tons (2.76 billion lbs) compared to 1.36 million metric tons (3.01 billion lbs) for all the United States in 2012 (USDA, 2013). For the population of U.S. citizens that do not live in those few states, finding high quality, local produce during the winter months can prove challenging.

The use of heated greenhouse structures, coupled with supplemental lighting (SL), may be helpful in meeting the demand for fresh, local produce during the coldest months of the year. Off-season production of berries is of high value to consumers; this is especially true when domestic production is at its lowest, and even if prices are higher (USDA, 2015). Producing an edible horticulture crop using this combination of factors is called controlled environmental agriculture (CEA) (Bradford et al., 2010; Hamano et al., 2016). Although moving production of high-value crops indoors, whether greenhouse or warehouse growing, presents its own challenges (e.g. structural and electrical costs, insect and disease pressures, and supplying nutrients), it also allows growers more control over climate variables. These characteristics can help to close the gap of seasonally unavailable produce for local consumers.

When growing in greenhouses in the winter, SL is usually necessary to supplement natural sunlight. Day lengths are also shorter during the cooler winter months. Traditionally, high intensity discharge (HID) forms of supplemental lighting (e.g. high-pressure sodium) have been used in greenhouses to allow for winter production, but light-emitting diodes (LEDs) have quickly become an alternative that growers are adopting (Park et al., 2014; Singh et al., 2015). LEDs typically produce little heat, are energy efficient, and wavelengths can be adjusted for each individual crop's growing requirements. LEDs present greenhouse growers with additional ways to explore expanded production and sustainability, as well as opportunities for off-season production (Massa et al., 2008; Morrow, 2008). Individual diodes that make up LED light fixtures range in their color spectrums (i.e. wavelengths), which are typically comprised of a combination of blue, red, far-red, and/or white. Specifically, the combination of red/blue and red/blue/white LEDs has been shown to increase overall photosynthetic pigments as well as the net photosynthetic rate (Pn) (Liu et al., 2011), and increased leaf area in cherry tomatoes (Son et al., 2018).

Sole-source (SS), single wavelength (SW) blue (475 nm) LEDs have been reported to increase individual strawberry size (2x on average) when compared to SS, single wavelength, red LEDs alone (Magar et al., 2018). Increased strawberry fruit yield and individual fruit size were reported when plants were grown under SS SW blue LEDs (Choi et al., 2015), as well as combinations of blue and red LEDs under growth chamber conditions, compared to red LEDs alone (Samuolienė et al., 2010). Increases in vegetative measurements, such as crown weight and crown diameter, have also been reported under SS blue and combined SS blue and red LEDs (Nadalini et al., 2017);(Wu et al., 2011).

Many cultivars of strawberry only flower and bear fruit during specific times of the year as a response to day length (e.g. short-day cultivars). This phenomenon is referred to as photoperiod response. However, certain strawberry cultivars produce flowers and fruit independent of day length. Day-neutral strawberry cultivars, unlike June-bearing (i.e. short day) cultivars, produce continuously if conditions are conducive to growth. In addition to being day-neutral, these cultivars are also remontant (i.e. blooming or producing a crop more than once in a given season). This is a highly desirable trait for growers since it ensures continuous harvests throughout the entire crop growth cycle. CEA strawberry production with supplemental lighting, coupled with optimum daytime growing temperatures (20°C − 24°C) (Kimura, 2008) has been shown to increase flower production in day-neutral strawberry cultivars (Nishiyama & Kanahama, 2000). It has also been demonstrated that the use of LEDs as supplemental overhead lighting improves overall berry fruit quality (e.g. degrees Brix (°Bx), flavor, and vitamin C) and yield when applied directly to the leaf canopy and fruits within a greenhouse environment (Hanenberg et al., 2016).

Studies investigating the optimum wavelengths and ratios of supplemental LED lighting for production of high-value crops, especially strawberries, have not been well documented (Hemming, 2011). Access to this information could present a large benefit to current and future strawberry producers, particularly with the increasing amounts of greenhouse and warehouse (i.e. sole source lighting) growing that has been seen over the last few years (Cherney, 2018). Commercially available fixtures currently on the market include different ratios and wavelengths of diodes that may have impacts on strawberry growth, fruit quality, and yield.

The objective of these experiments was to evaluate the efficacy of three commercially available LED SL top light bars with different blue, red, far-red, and white ratios for strawberry production in a greenhouse during two off-season periods (October – December and January – March) in northern Colorado (40.5653° N, 105.0850° W). Further, we evaluated two day-neutral cultivars of strawberries under these conditions. Crop parameters measured included overall berry quality (soluble solids content (°Bx), fruit marketability) total yield, individual fruit size, fruit number, crown number, vegetative biomass, and stolon production. We hypothesized that the addition of LED supplemental lighting, would cause an increase in all measured parameters. It was also hypothesized that LED light bars with higher densities of blue and red wavelengths would increase yield and soluble solids content of the fruit. Lastly, we expected the two day-neutral strawberry cultivars to respond similarly to the three supplemental LED lighting treatments.

1.2 Materials and Methods

Off-season greenhouse strawberry trials were conducted at Colorado State University Horticulture Center greenhouses (Fort Collins, CO) during two off-season production periods: naturally shortening days (Experiment 1, October – December 2017) and naturally lengthening days (Experiment 2, January – April 2018), to investigate the effects of LED top lights on the growth, yield, and fruit quality of two day-neutral strawberry cultivars.

1.2.1 Plant Material

Strawberry (*Fragaria* X *ananassa* Duch. ‘Albion’ and ‘San Andreas’) plugs were received from a commercial grower (McNitt’s Growers, Carbondale, IL) on 21 September 2017, and used for Experiment 1. Plugs consisted of stolon cuttings rooted in a soilless media. Plugs were transplanted into bato buckets (‘Meter Trough’; 99 cm x 17.7 cm x 18.5 cm; 6.22 L volume; AMA Plastics, Kingsville, ON, Canada), and extras were planted into 8.9 cm (3.5 in) pots for future use. Each bato bucket was considered an experimental unit and was planted with six plants, 15 cm apart, in a coco-coir and peat-based growing substrate (BVB BC5 Strawberry Mix; AMA Plastics). Three batos of both cultivars, ‘Albion’ and ‘San Andreas’, were randomly assigned to each of the four LED light treatments, and arranged in a randomized complete block design (RCBD) (north-south) across three rolling benches (replications) (Fig. 1). Plants were irrigated using individual drip lines and 1.98 L (0.5 gallon)/hour emitters, with 90-125 mL per day, depending on watering needs. Electrical conductivity (EC) and pH of influx were measured twice a month using a digital EC and pH meter (MC110 pH Monitor, Milwaukee Instruments, Inc., Rocky Mount, NC; MC310 EC Monitor, Milwaukee Instruments, Inc.) to ensure a range of 0.9-1.2 mS/cm^2 and 5.5-6.5, respectively. Plants were fertigated with a water-soluble nutrient concentrate containing 8% N, 12% P, 32% K, 0.5% Mg, 0.25% S (Hydro-Gardens Strawberry Formula, Colorado Springs, CO), and $Ca(NO_3)_2$ (0.95g/L for 100x concentrate). Average greenhouse temperatures were set to daytime temperatures of 20°C and 15°C at night, with a range of relative humidity (RH) at 40-60%.

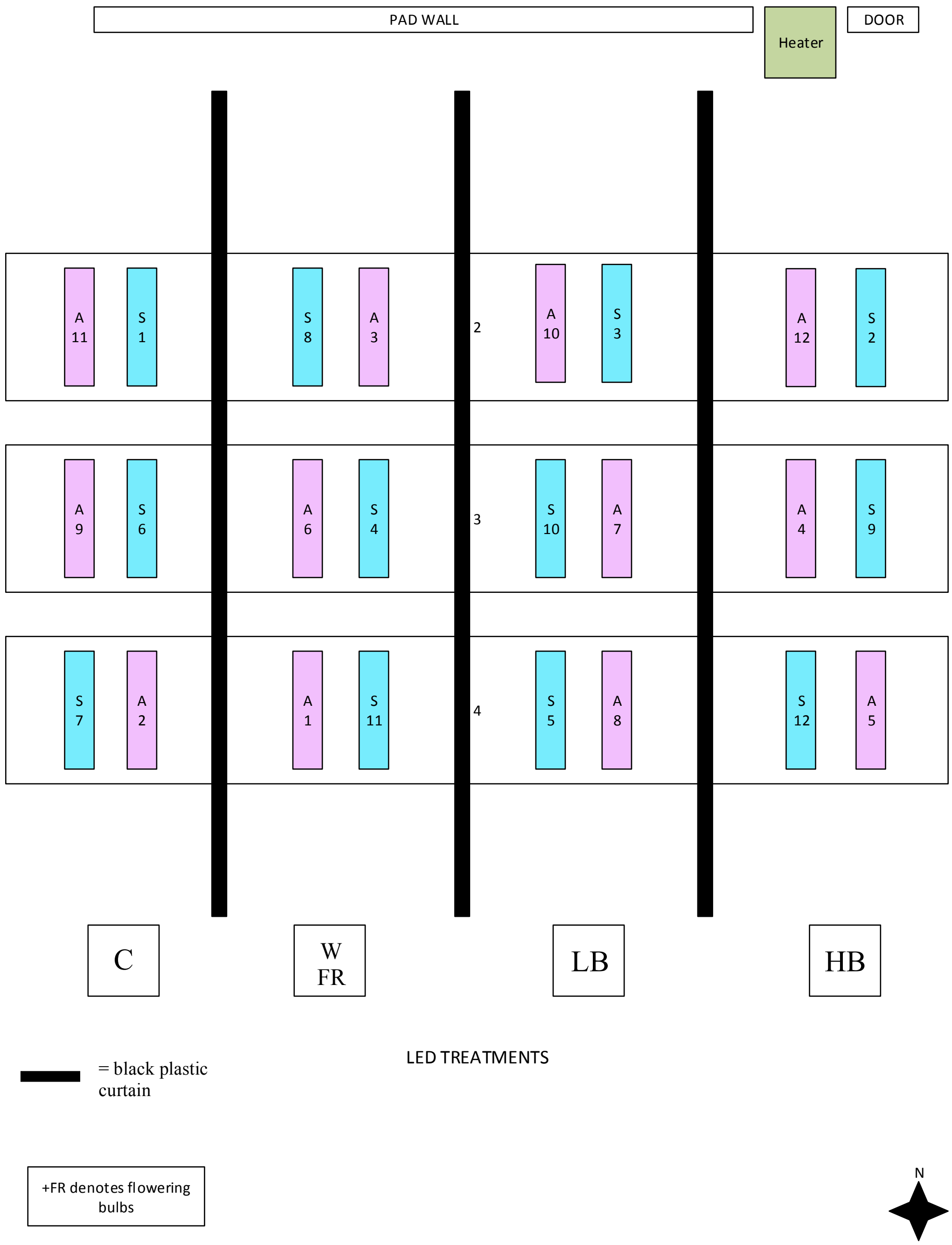

Figure 1. Layout of experimental units (i.e. bato buckets) placement within LED treatments in a greenhouse. Replications with A = 'Albion' plants, S= 'San Andreas' plants, with replication number identifier. LED treatments: FR= far-red, DR = deep red, HB = high blue, LB = low blue, and W = white (with FR integrated into light bar).

Flowers were hand-pollinated using a small, short-bristled brush at anthesis to supplement pollination that likely occurred within the greenhouse due to ventilation and fan airflow.

For Experiment 2, extra plugs from the first experiment were placed into a commercial cooler at 4.4°C (40°F) from October 2017 – January 2018. Plants were then transferred from the cooler and allowed to acclimate under greenhouse conditions for 7 days before being transplanted into bato buckets (Meter Trough; AMA Plastics). Once acclimated plugs were planted, they were re-randomized and irrigated using the same protocols as Experiment 1.

Common greenhouse pests included two-spotted spider mite, thrips, aphids, and a fungal disease, powdery mildew. Insects and powdery mildew were managed using biological controls (Swirskii-System *(Amblyseius swirskii)*, Californicus-System *(Amblyseius fallacis)*, BioBest, Leamington, ON, Canada) and potassium bicarbonate (sprayed weekly), respectively.

1.2.2 Supplemental Lighting Treatments

A different LED top light was applied to each treatment row (LED light bars were not used in the control) (Figs. 2 & 3) and run continuously for 16 h/day (0300 to 1700 HR). LED light bars were individually measured in isolation (i.e. within greenhouse at night) at 2.13 m away, using a spectroradiometer (SS-110, Apogee Instruments, Inc., Logan, UT) to determine wavelength peaks photon flux density (*PFD*) of blue and red diodes (Fig. 4). Greenhouse photosynthetic photon flux density (*PPFD)* of 90 $\mu mol \cdot m^{-2} \cdot s^{-1}$ was measured and the daily light integral (DLI) of 7-10 $mol \cdot m^{-2} \cdot s^{-1}$ was calculated at plant height using a quantum sensor (LI-190R, LI-COR, Inc., Lincoln, Nebraska). Each LED treatment was positioned above the plants from north to south across the top of a set of rolling benches (running east to west) and was separated by 6 mm black plastic curtains (1.5 m in height), to create individually lighted areas (Fig. 2). Depending on the treatment, the light fixtures were placed at varying heights to ensure a constant PPFD (90 µmol·m^{-2}·s^{-1}) and DLI were obtained in each lighted row. For Experiment 2, lighted treatments were re-randomized within the same greenhouse bay and benches.

LED light treatments (Figs. 1 & 2) were composed of commercial fixtures (175 - 215W) and defined by the manufacturer's labels as:

- Control = flowering bulbs alone (Deep Red/White/Far-Red);
- WFR = Deep Red/White/Far Red - Medium Blue + flowering bulbs;
- LB = Deep Red/Blue - Low Blue + flowering bulbs;
- HB = Deep Red/Blue - High Blue + flowering bulbs.

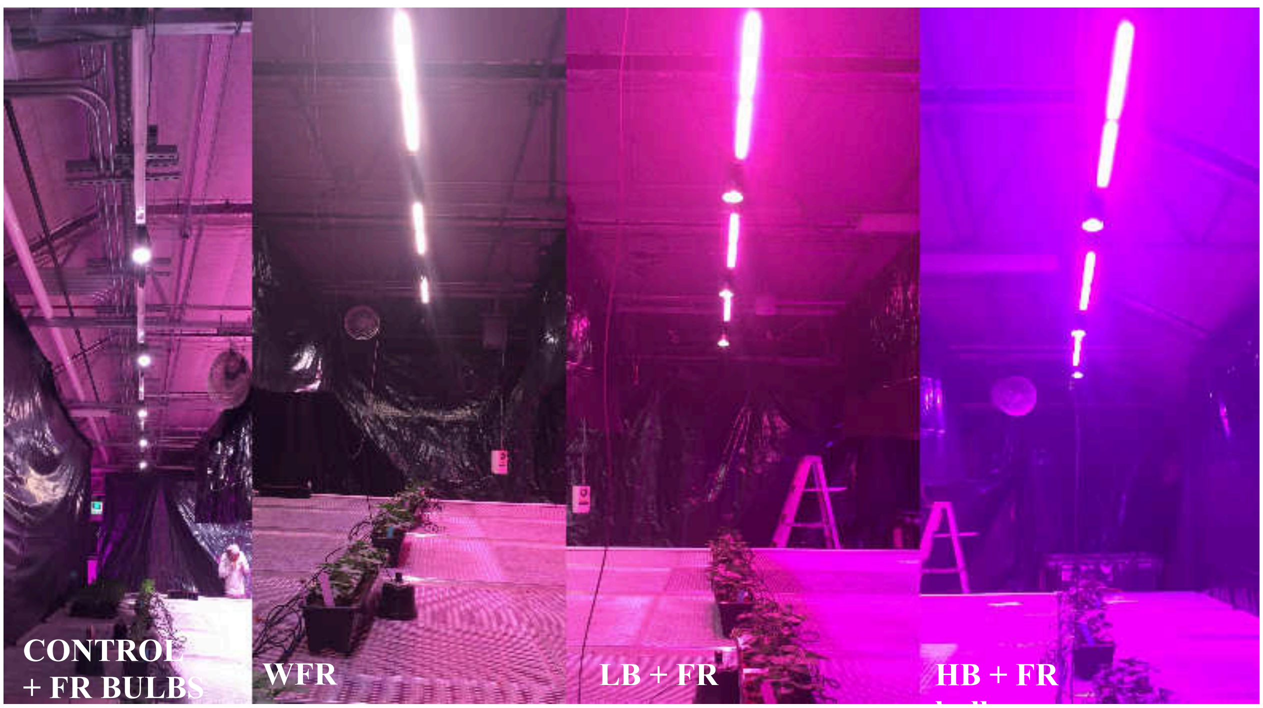

Figure 2. LED Lighting treatments at night (left to right, Control with flowering bulbs, WFR, LB with flowering bulbs, and HB with flowering bulbs).

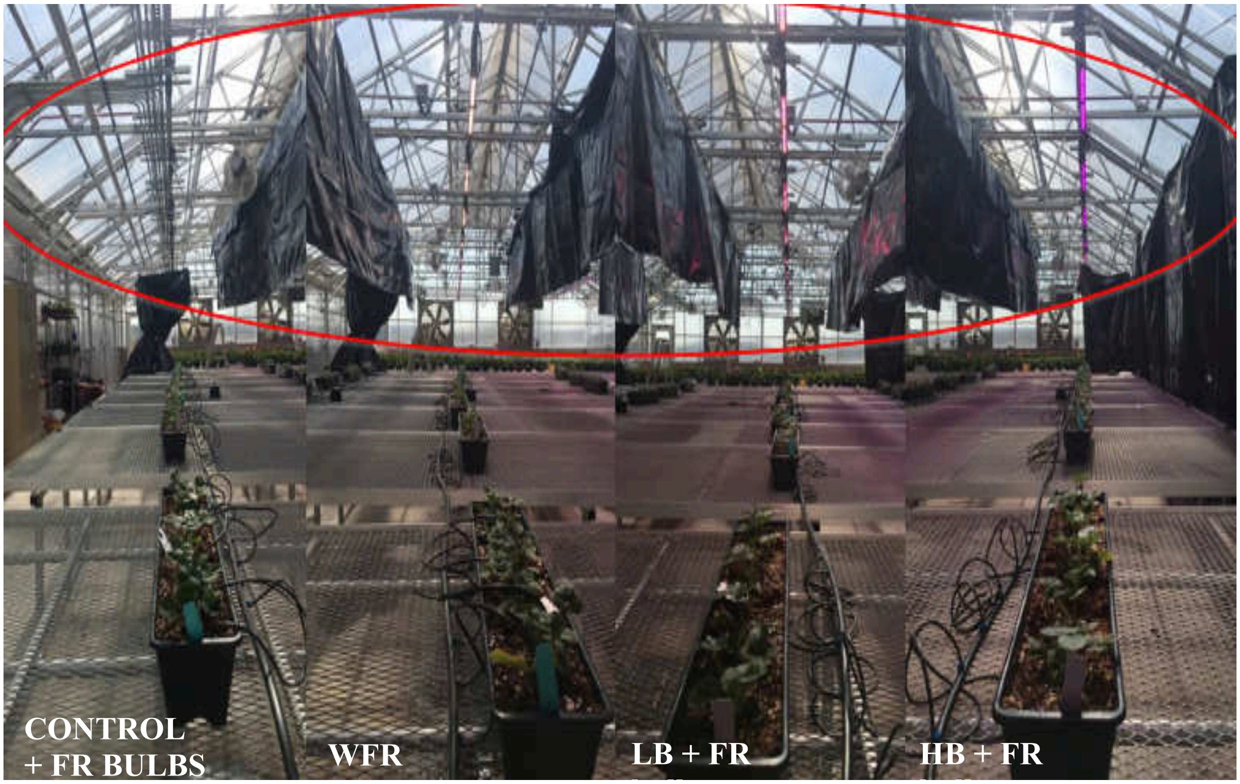

Figure 3. LED Lighting treatments and tarping during daytime (left to right, Control with flowering bulbs, WFR, LB with flowering bulbs, and HB with flowering bulbs).

1.2.3 Fruit yield and quality measures: Soluble solids content, fruit number and weight

During the time of peak harvest, 2-3 individual strawberries were picked from each experimental unit, macerated, and homogenized. Juice was separated from the fruit solids with cheese cloth to obtain a liquid sample and placed onto a digital refractometer (Reichert™ AR200, Fisher Scientific, Hampton, NH), that was calibrated with distilled water. Measurements were taken at room temperature using the Brix-TC (temperature compensated) setting and recorded for each experimental unit. Strawberry fruits were individually weighed and assigned a USDA grade individually throughout the growing season to quantify overall reproductive yield and marketable yield (USDA, 2006).

1.2.4 Leaf area, crown number, and stolon measurements

After the final fruit harvest, plants were cut to the base of the crown and fruit pedicels, leaves (petioles included), and stolons were separated and weighed for each experimental unit. Leaves were scanned with a leaf area meter (LI-3100C Area Meter, LI-COR, Inc., Lincoln, Nebraska), and placed back with the petioles into individual paper bags. Plant material was placed in an oven at 70°C for 48 hours, then weighed to determine dry biomass. The number of crowns in each experimental unit were counted at the beginning and end of experiments to characterize overall vegetative growth of the plants.

1.2.5 Statistical Analysis

Data were analyzed as a randomized complete block design, using a factorial analysis of variance carried out in R-Studio platform (Version 3.3.1). A linear model (Model = lm(Response ~ Block + Treatment*Cultivar, data)($y = \mu + B + T + C + T \times C$) using the lsmeans package was used and significance was reported at $\alpha = 0.05$. Data were assessed using the Shapiro-Wilk test for assumptions of normality ($\alpha = 0.05$). Letters within figures symbolize statistically significant differences between treatments. Main effects of treatment and main effects of cultivar are shown when data analyses are significant and did not reveal an interaction. Block effects are reported when significant. Experiment 1 and Experiment 2 were analyzed separately, except for individual strawberry fruit weight, which was combined due to similarities within the data.

1.3 Results

1.3.0 Photon Flux Density of Individual LED Top Light Bars

Spectroradiometer readings at bench height (2.13 m) showed measurements of the LB and HB LED lighting treatments at 455nm (blue) and 665nm (red) light peaks (Fig. 4). The WFR LED lighting treatment had a measured blue peak at 440nm, red peak at 665nm, and a far-red peak at 735nm. The highest red and blue photon count was measured within the HB LED treatment at 0.75 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at 455nm and 2.75 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at 665nm. The PFD of the LB LED treatment measured at 0.25 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at 445nm and 2.60 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at 665nm, and the WFR LED treatment at 0.35 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at 445nm, 1.75 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at 665nm, and 0.20 $\mu mol \cdot m^{-2} \cdot s^{-1}$ 735nm.

1.3.1 Experiment 1 (Oct. – Dec. 2017)

Fruit Quality Parameters: SSC, Yield, Marketable Fruit Number

For fruit yield and fruit quality (soluble solids content (SSC)), there were no cultivar*treatment interaction and there was a significant main effect of both cultivar and treatment. SSC for 'Albion' berries in low blue (LB) and high blue (HB) and 'San Andreas' berries in HB increased in size compared to the control (Fig. 5). Average total yield (g) of all marketable strawberry fruits for each treatment (HB, LB, WFR) were statistically higher than the control (Fig. 7). The average number of marketable fruit were statistically higher than the control in all lighted treatments for both cultivars (Fig. 8). Cultivars were combined as an analysis of variance revealed that there was a main effect of treatment, but not cultivar.

Vegetative Parameters: Leaf Area, Crown Number, Stolon Weight

There was a significant main effect for both treatment and cultivar, with no interaction. Leaf area of 'San Andreas' plants in all of the lighted treatments (WFR, LB, HB) were significantly higher than the leaf area of the control. 'Albion' plants in the HB and LB LED treatments were also significantly higher than the control (Fig. 6). Both cultivars in Experiment 1 responded to the lighting treatments by increasing leaf area, with the greatest area in the LB and HB lighted treatments.

There was a significant interaction between cultivars and treatments, and significant main effects of both cultivar and treatment for crown number measurements. The average number of 'San Andreas' strawberry crowns was statistically higher than the control in the HB, LB, and WFR LED treatments. Average numbers of 'Albion' crowns were significantly higher only in the WFR lighted treatment (Fig. 9).

A significant main effect of treatment and cultivar, as well as an interaction, was revealed within vegetative stolon production measurements using an analysis of variance. An increase in stolon production was seen in 'Albion' strawberry plants within each lighting treatment compared to the control, while 'San Andreas' strawberry plants showed very little runner production overall (Fig. 10).

1.3.1.1 Photon Flux Measurements of LED Light Treatments

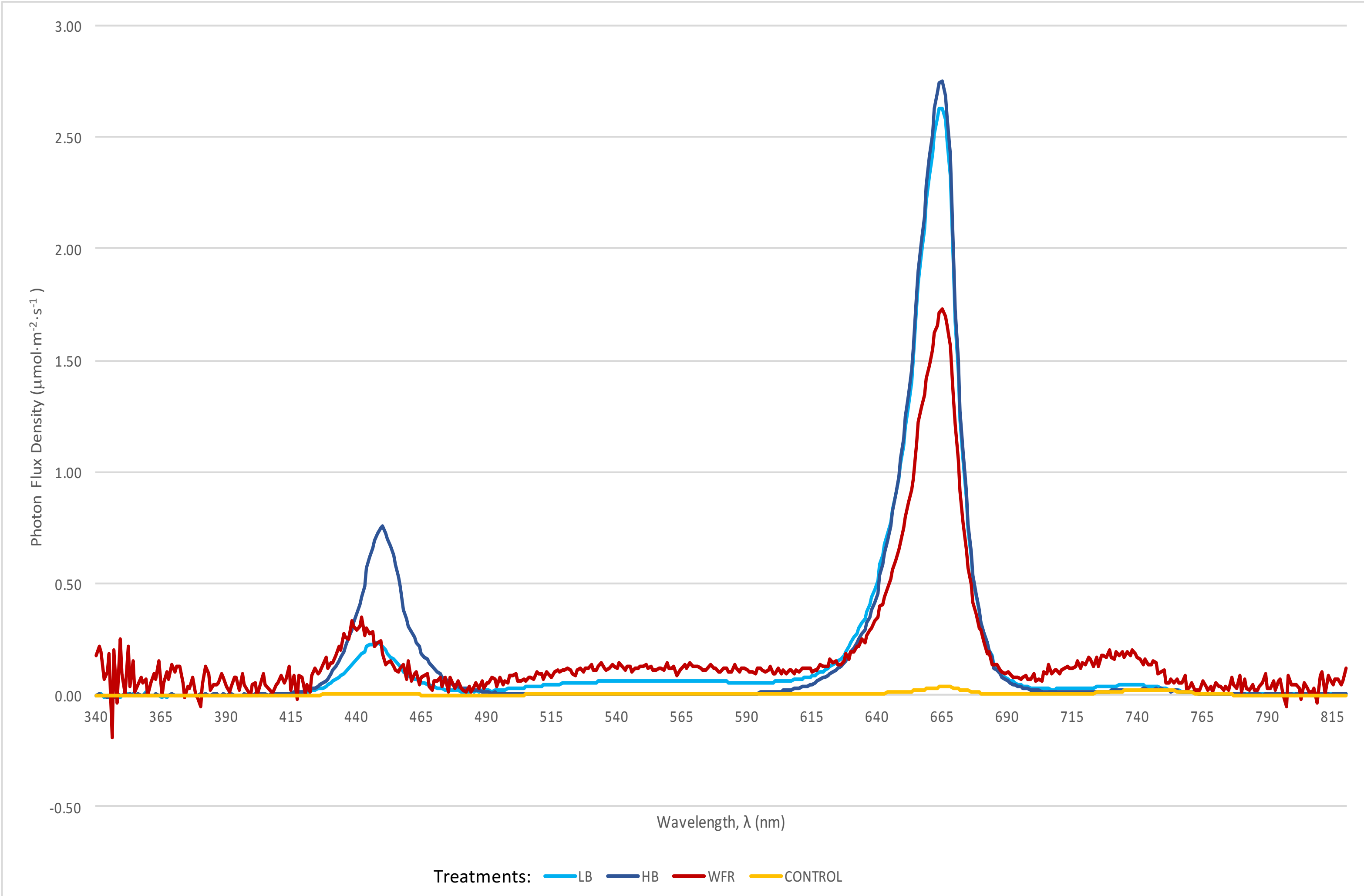

Figure 4. Photosynthetic photon flux density of individual LED top lights in an isolated environment (i.e. individually separated treatments at night).

1.3.1.2 Soluble Solids Content of Greenhouse-Grown Strawberries

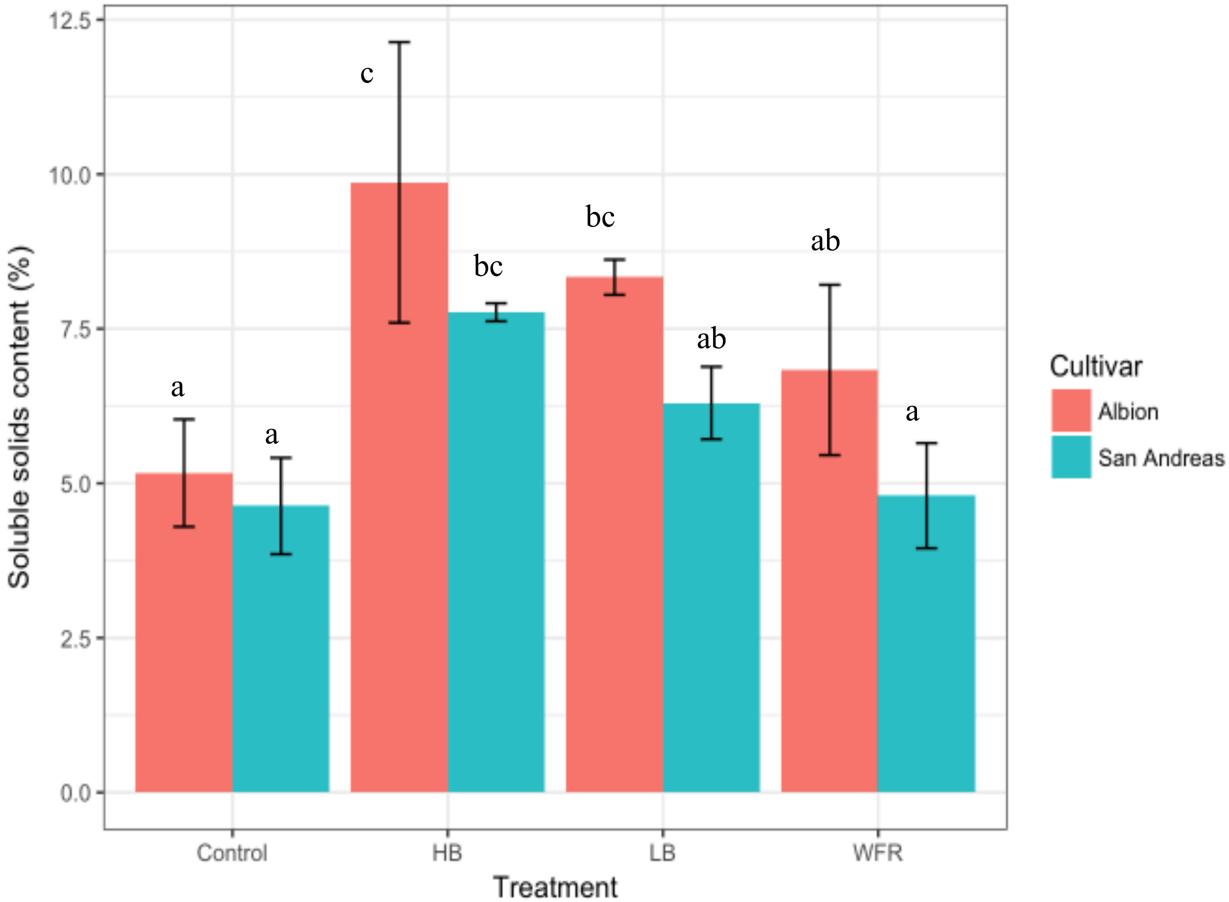

Figure 5. Analysis of mean soluble solids content (%) of strawberry cultivars 'Albion' and 'San Andreas' in response to LED lighting treatments (Control, HB =High Blue, LB = Low Blue, and WFR = White/Far-Red) in Experiment 1 (Oct. 2017 – Dec. 2017) in Fort Collins, CO. Standard error (SE) bars indicate the mean $\pm_{SE}$ (n = 3). Different letters (a, b, & c) symbolize statistically significant differences between treatments.

1.3.1.3 Leaf Area of Greenhouse-Grown Strawberries

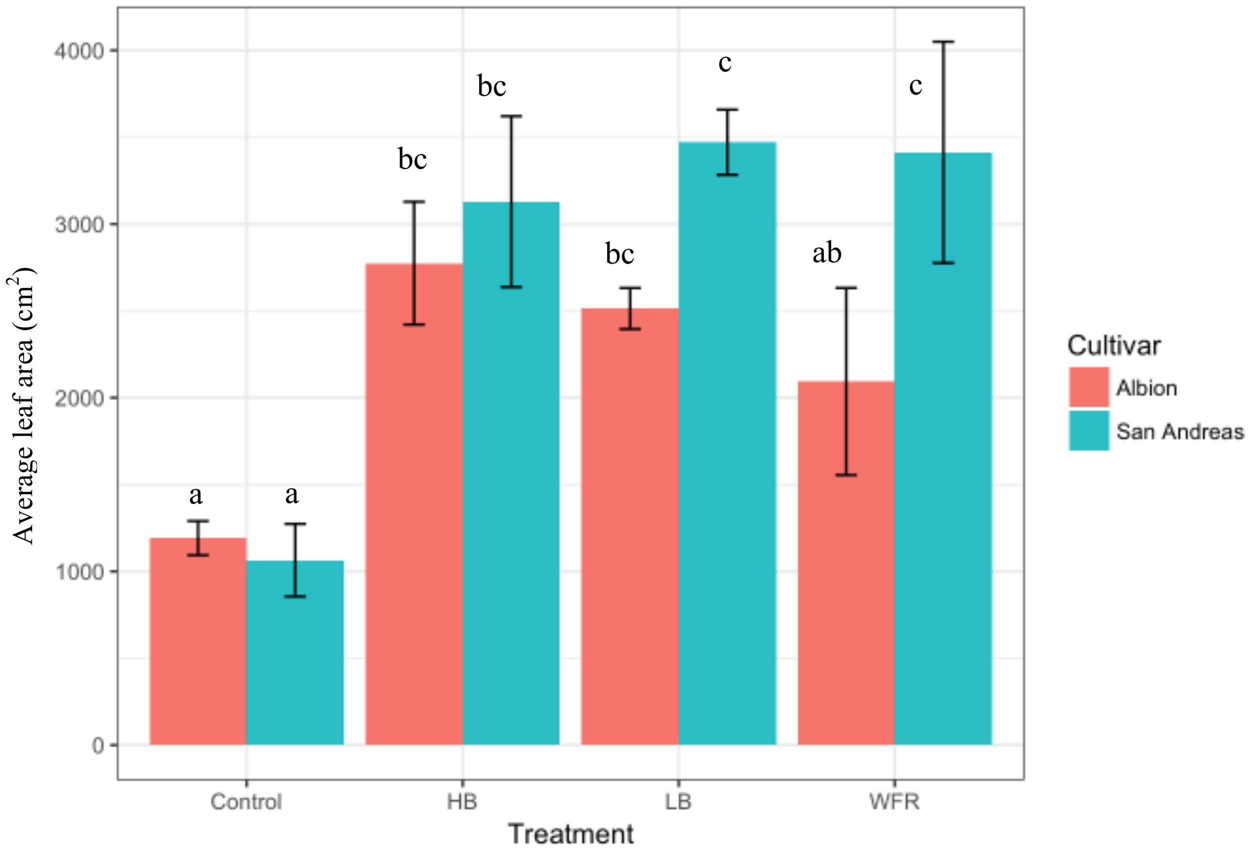

Figure 6. Analysis of mean leaf area of the inner 4 plants (within a replication/bato) of cultivars 'Albion' and 'San Andreas' in response to treatments (Control, HB =High Blue, LB = Low Blue, and WFR = White/Far-Red) in Experiment 1 (Oct. 2017 – Dec. 2017) in Fort Collins, CO. Standard error (SE) bars indicate the mean $\pm_{SE}$ (n = 3). Different letters (a, b, & c) symbolize statistically significant differences between cultivars.

1.3.1.4 Overall Yield of Greenhouse-Grown Strawberries

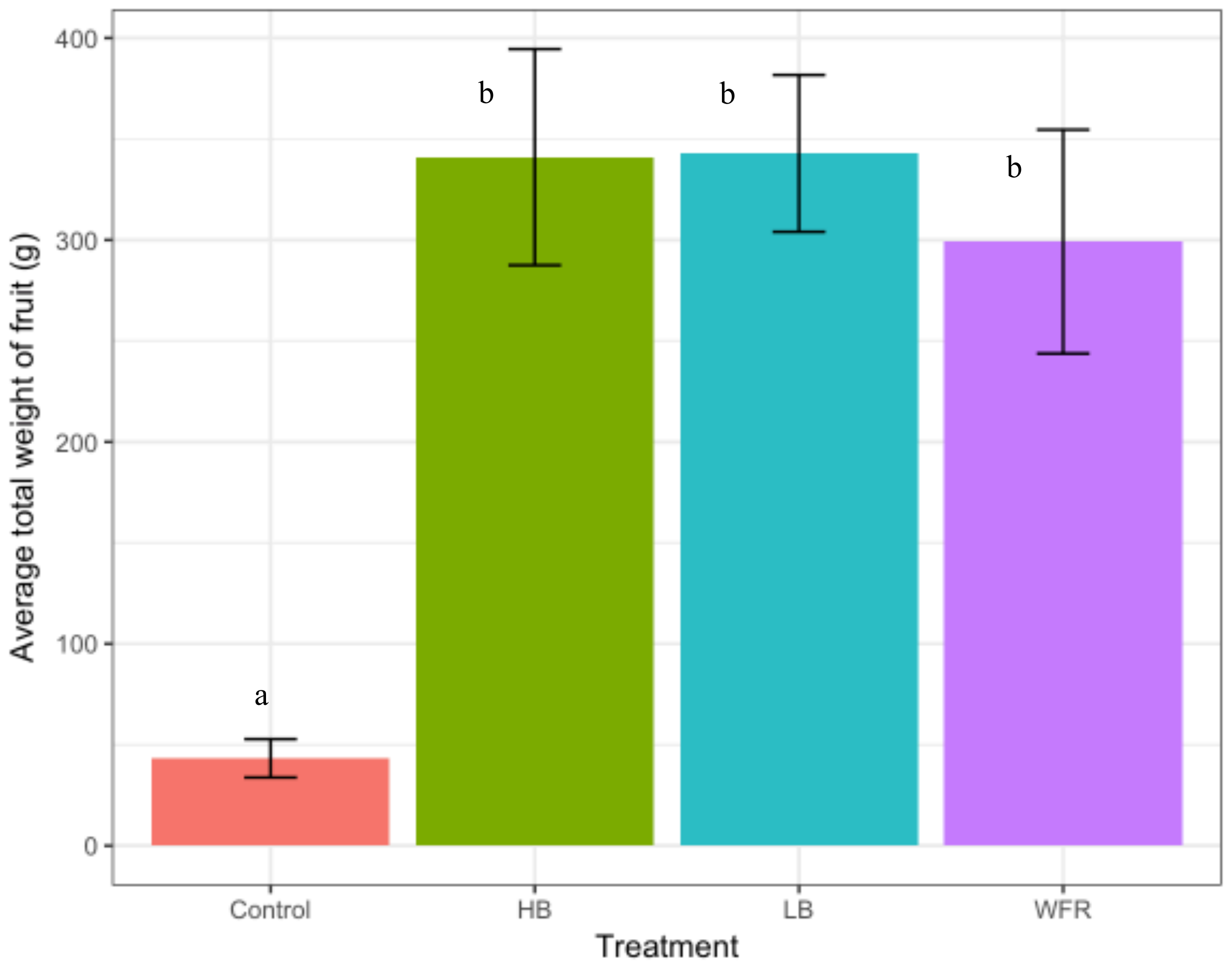

Figure 7. Analysis of mean total weight (g) of all marketable fruit of both cultivars 'Albion' and 'San Andreas' combined, in response to treatments (Control, HB =High Blue, LB = Low Blue, and WFR = White/Far-Red) in Experiment 1 (Oct. 2017 – Dec. 2017) in Fort Collins, CO. Standard error (SE) bars indicate the mean $\pm_{SE}$ (n = 6). Averages for all treatments are displayed as the cultivar main effect was not significant. Different letters (a & b) symbolize statistically significant differences between treatments.

1.3.1.5 Marketable Fruit Count of Greenhouse-Grown Strawberries

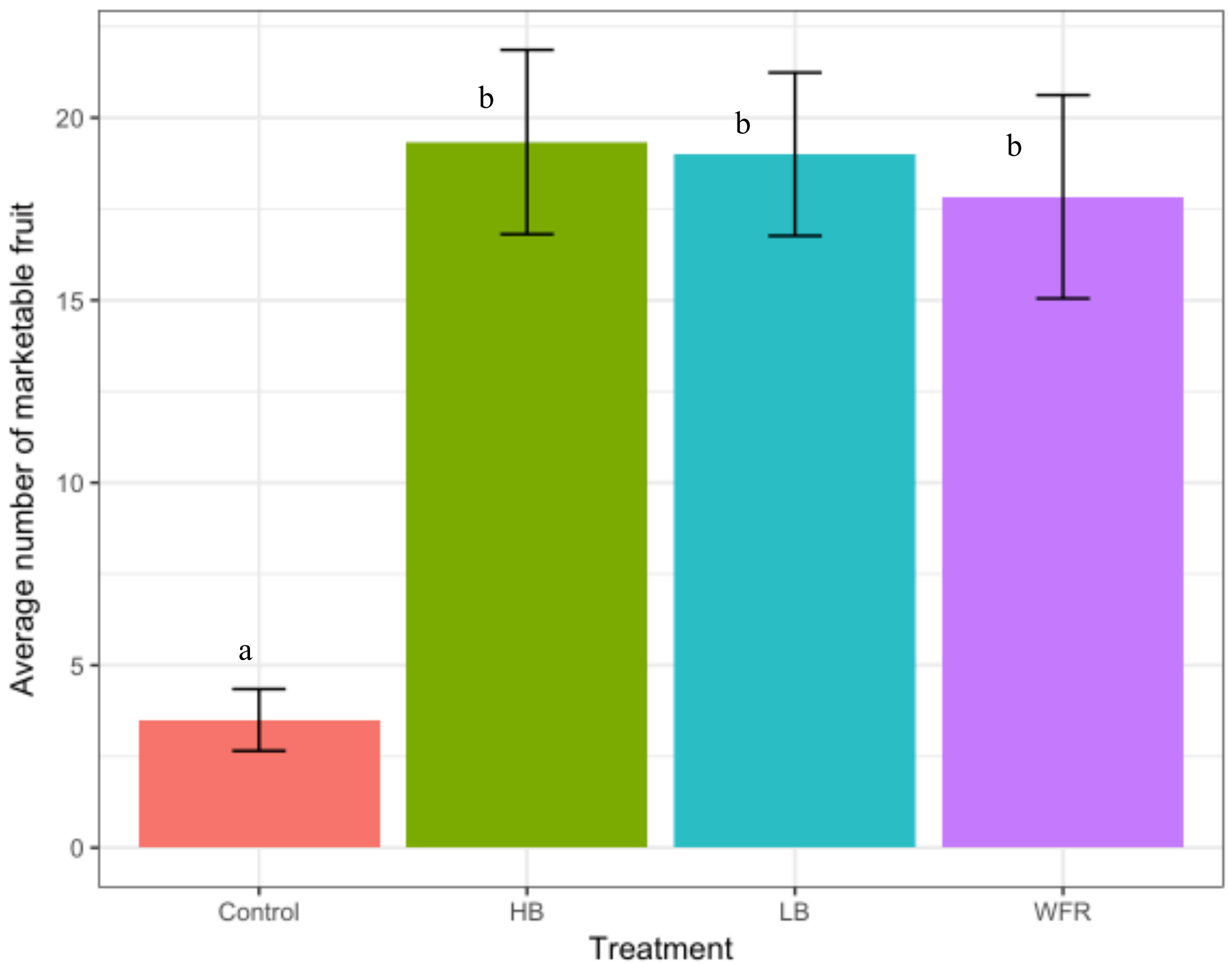

Figure 8. Analysis of the mean number of all marketable fruit of both cultivars 'Albion' and 'San Andreas' combined, in response to treatments (Control, HB =High Blue, LB = Low Blue, and WFR = White/Far-Red) in Experiment 1 (Oct. 2017 – Dec. 2017) in Fort Collins, CO. Standard error (SE) bars indicate the mean $\pm_{SE}$ (n = 6). Averages for all treatments are displayed as the cultivar main effect was not significant. Different letters (a & b) symbolize statistically significant differences between treatments.

1.3.1.6 Strawberry Crown Numbers of Greenhouse-Grown Strawberries Plants

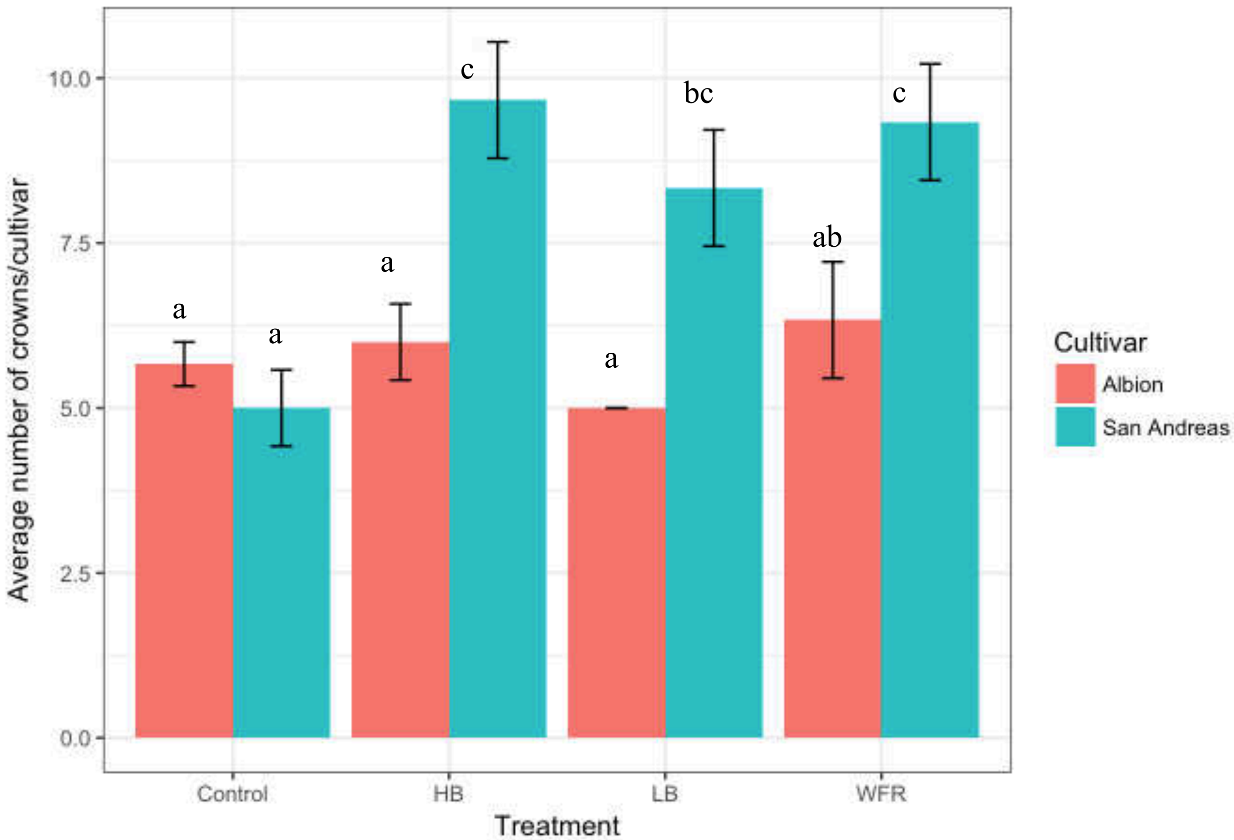

Figure 9. Analysis of the mean number of strawberry crowns/replication of cultivars 'Albion' and 'San Andreas' in response to treatments (Control, HB =High Blue, LB = Low Blue, and WFR = White/Far-Red) in Experiment 1 (Oct. 2017 – Dec. 2017) in Fort Collins, CO. Standard error (SE) bars indicate the mean $\pm_{SE}$ (n = 3). A significant interaction between cultivar and treatment effects was noted. Different letters (a, b, & c) symbolize statistically significant differences between cultivars and treatments.

Note: 'Albion' did not elicit an increase crown number in response to the LED top lights. 'San Andreas' responded to all three LED treatments in a significant way.

1.3.1.7 Stolon Wet Weight of Greenhouse-Grown Strawberries Plants

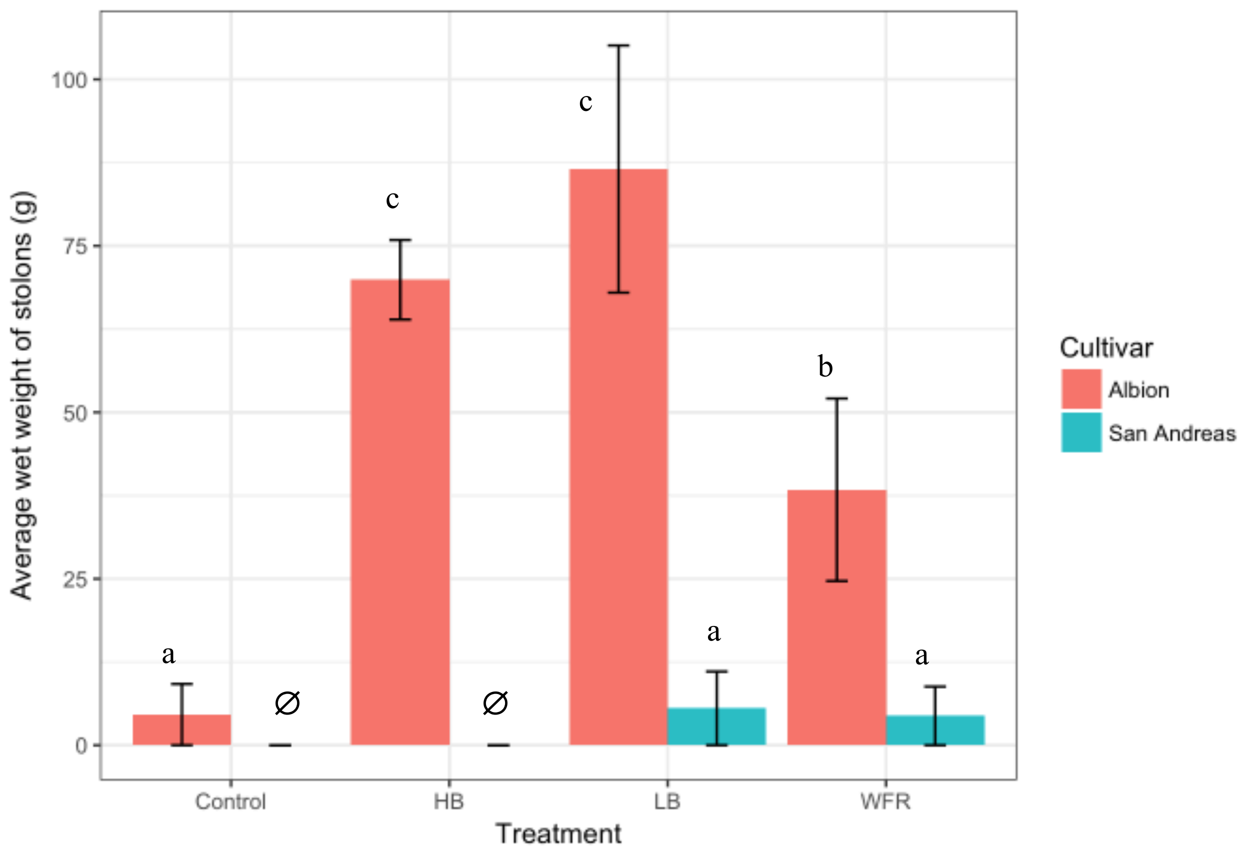

Figure 10. Analysis of the mean stolon weight (grams) of cultivars 'Albion' and 'San Andreas' in response to treatments (Control, HB =High Blue, LB = Low Blue, and WFR = White/Far-Red) in Experiment 1 (Oct. 2017 – Dec. 2017) in Fort Collins, CO. Standard error (SE) bars indicate the mean $\pm_{SE}$ (n = 3). Averages for both cultivars and all treatments are displayed, although a significant interaction between cultivar and treatment effects was noted. Different letters (a, b, & c) symbolize statistically significant differences between cultivars and treatments. Note: 'San Andreas' replications in Control and HB LED treatments produced no stolons (i.e. -0 g. stolons).

1.3.2 Experiment 2 (Jan. – April 2018)

A significant main effect of cultivar, but not treatment, allowed for treatments to be combined for soluble solids content in Experiment 2. ‘Albion’ berries were significantly sweeter with a higher SSC measurement than ‘San Andreas’ (Fig. 11).

Treatments were also combined for average leaf area measurements, as ‘San Andreas’ plants had significantly larger leaves than ‘Albion’ plants (4321 cm^2 and 2855 cm^2, respectively). There was no significant difference in leaf area between LED lighting treatments (Fig. 12).

Both cultivars responded similarly to naturally lengthening days in Experiment 2 with increased stolon production in all lighted treatments (Fig. 13). Cultivars were combined as there was no significant difference between ‘Albion’ and ‘San Andreas’. The LB and HB treatments produced an average weight (g) of 2.6x more stolon vegetation than the control (168 g and 166 g vs. 63 g, respectively).

There were no significant differences measured between cultivars or LED treatments for overall marketable yield, marketable fruit number, or crown number during the lengthening days of Experiment 2.

1.3.2.1 Soluble Solids Content of Greenhouse-Grown Strawberries

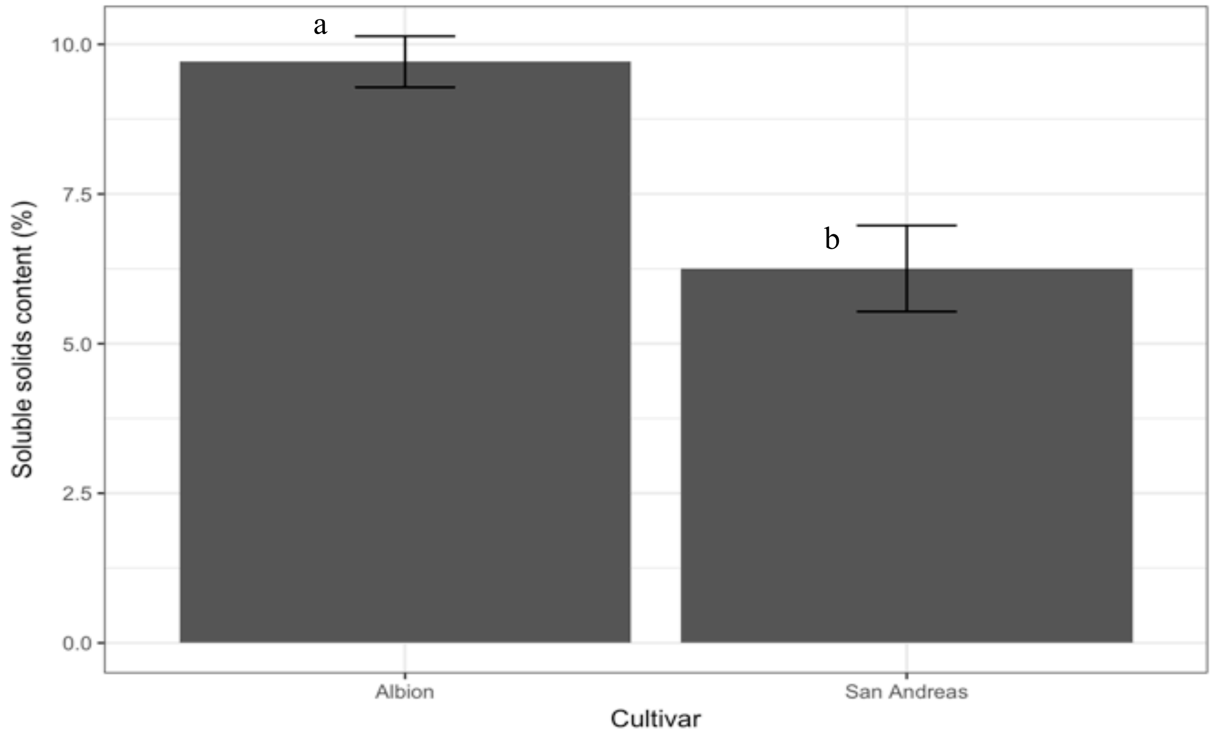

Figure 11. Analysis of mean soluble solids content (%) of cultivars 'Albion' and 'San Andreas' in Experiment 2 (Jan. 2018 – April 2018) in Fort Collins, CO. Standard error (SE) bars indicate the mean $\pm_{SE}$ (n = 12). Averages for both cultivars are displayed as the treatment main effect was not significant. Different letters (a & b) symbolize statistically significant differences between cultivars.

1.3.2.2 Leaf Area of Greenhouse-Grown Strawberries Plants

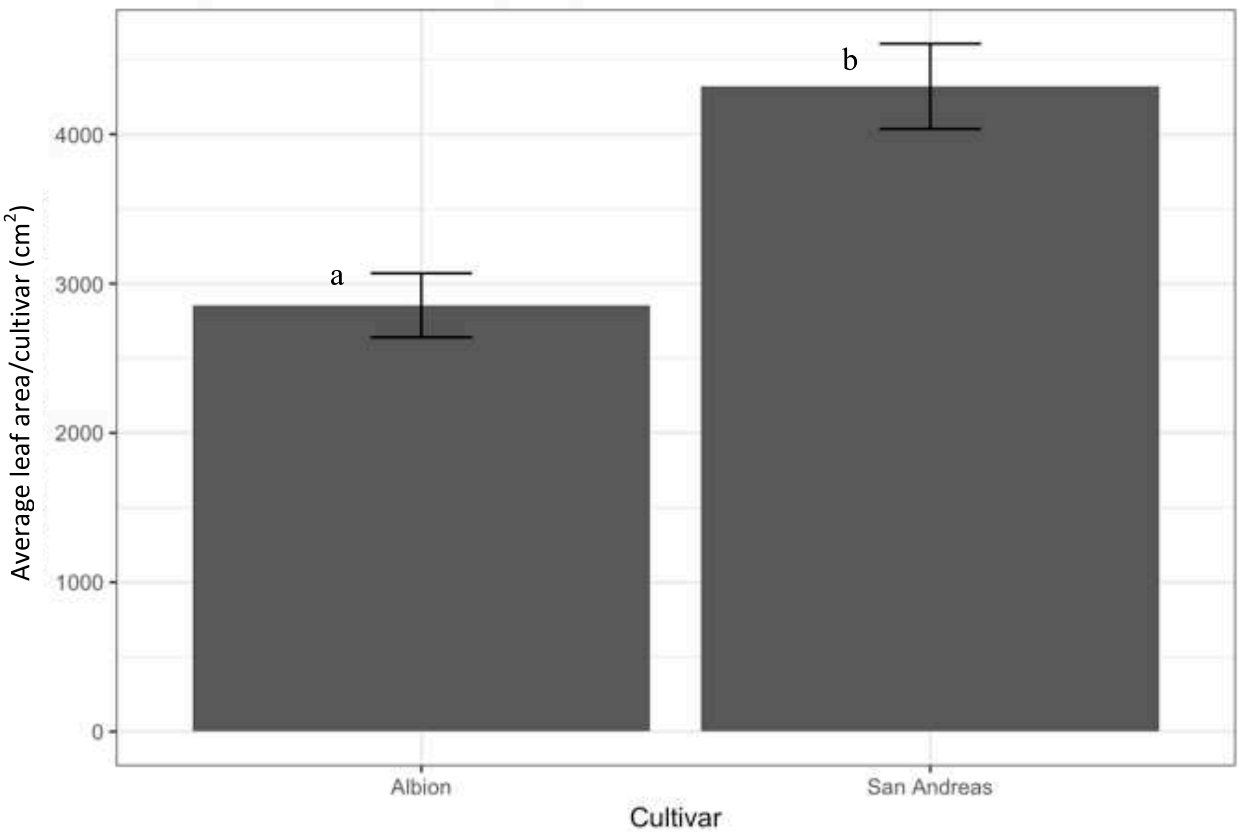

Figure 12. Analysis of mean leaf area (cm^2) of the inner 4 plants (within in a replication/bato) of cultivars ‘Albion’ and ‘San Andreas’ in Experiment 2 (Jan. 2018 – April 2018) in Fort Collins, CO. Standard error (SE) bars indicate the mean $\pm_{SE}$ (n = 12). Averages for both cultivars are displayed as the treatment main effect was not significant. Different letters (a & b) symbolize statistically significant differences between cultivars.

1.3.2.3 Stolon Wet Weight of Greenhouse-Grown Strawberries Plants

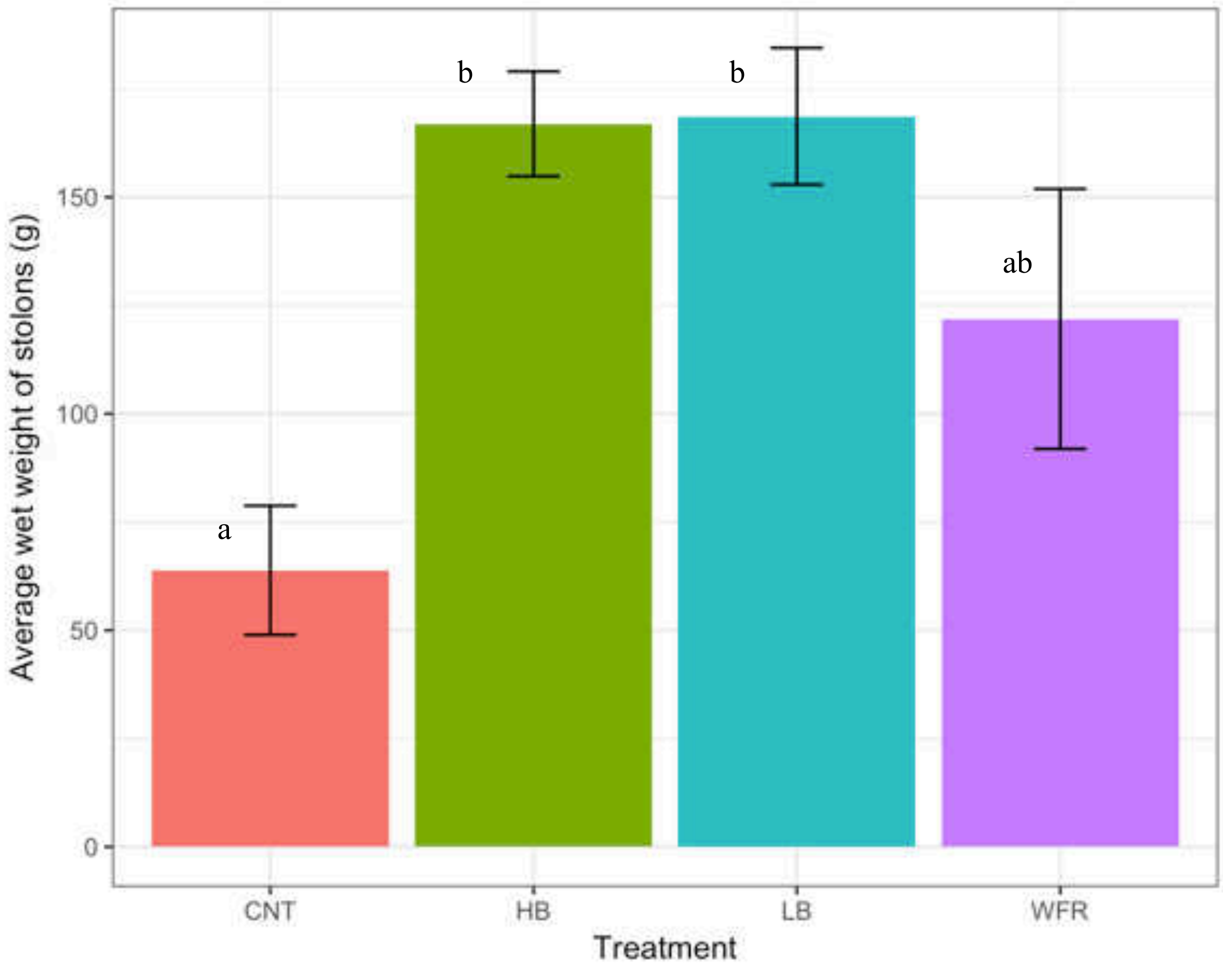

Figure 13. Analysis of the mean stolon weight (g) of both cultivars 'Albion' and 'San Andreas' combined, in response to treatments (Control, HB =High Blue, LB = Low Blue, and WFR = White/Far-Red) in Experiment 2 (Jan. 2018 – April. 2018) in Fort Collins, CO. Standard error (SE) bars indicate the mean ± $_{SE}$ (n = 6). Averages for all treatments are displayed as the cultivar main effect was not significant. Different letters (a & b) symbolize statistically significant differences between treatments.

1.3.3 Combined Experiment 1 & 2: Individual Strawberry Fruit Yield/Weight Measurements

Data from Experiment 1 and Experiment 2 were combined due to similar treatment responses. There was a significant main effect for both cultivar and treatment, but no interaction in both experiments. Individual 'San Andreas' berries in the LB and HB LED treatments were significantly larger than the control, but not from each other. 'Albion' berries in treatment groups HB and LB were similar in weights and significantly larger than the control group (Fig. 14).

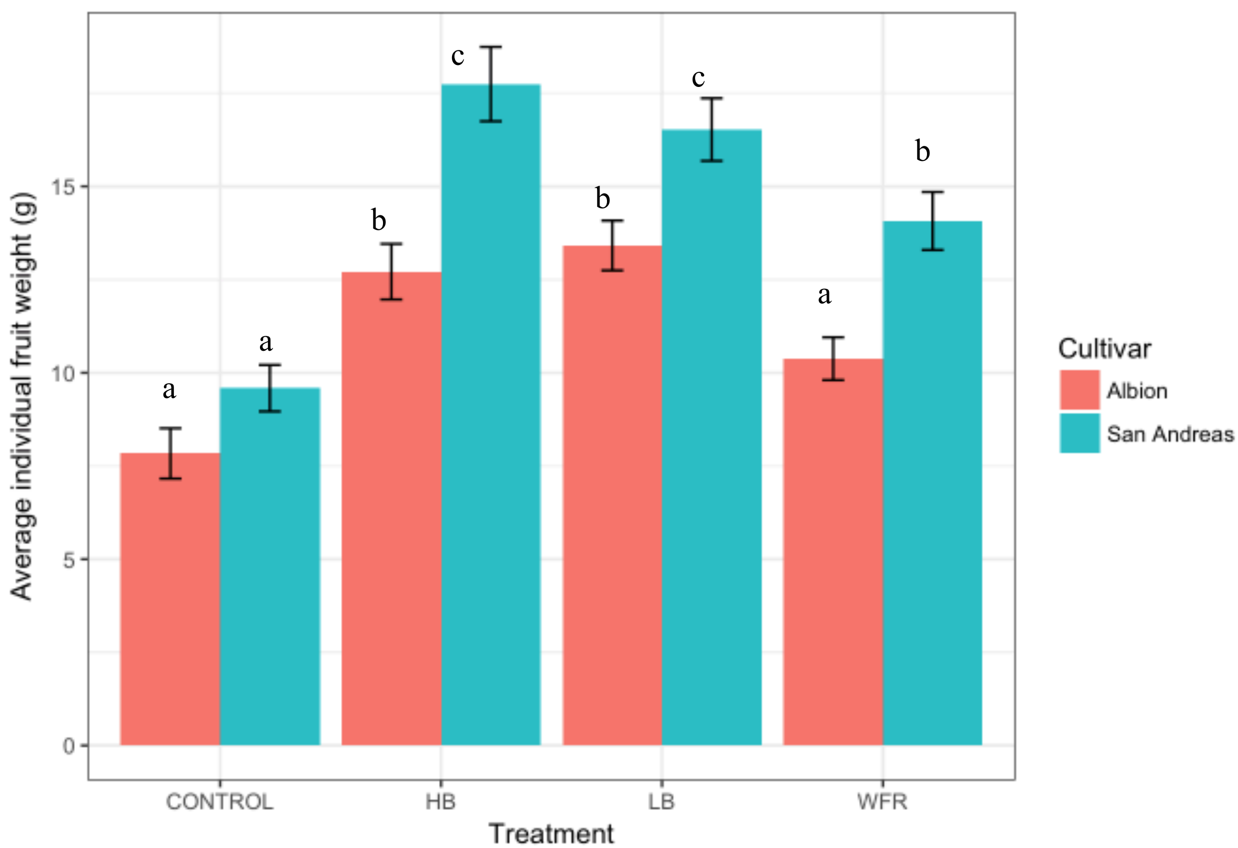

Figure 14. Mean individual strawberry fruit weight (g) of 'Albion' and 'San Andreas' in response to LED treatments (Control, HB =High Blue, LB = Low Blue, and WFR = White/Far-Red) in Fort Collins, CO. Data were combined for Experiment 1 & Experiment 2 (Oct. 2017 – Dec. 2017, Jan. 2018-April 2018). Standard error (SE) bars indicate the mean $\pm_{SE}$. Different letters (a, b, & c) symbolize statistically significant differences between cultivars.

1.4 Discussion

Supplemental lighting is a key factor that can allow growers to produce off-season food crops despite naturally short days (Dorais, 2003). In this study, however, there appeared to be a different response to the shortening days of Experiment 1 compared to the lengthening days of Experiment 2 for most factors measured. Specifically, strawberry individual fruit weight, total yield, and SSC were improved with the use of HB and LB LEDs during shortening days of Experiment 1. In addition, individual fruit weights increased in the HB and LB LED treatments in both experiments. Other studies have reported similar findings of increased weight of reproductive structures (flowers and fruits) when using sole-source (SS), single-wavelength (SW) blue (470 nm) LED lighting in a greenhouse environment (Magar et al., 2018). Increased fruit yield has also been reported by Choi et al. (2015) where the largest yields were harvested under greenhouse conditions with SL treatments of SW blue (448 nm) LED lighting and a combination of blue (448nm) and red (634 and 665 nm) at a 3:7 ratio, compared to red SL LED (634 and 665 nm) lighting alone. Yoshida et al. (2016) described accelerated harvests due to earlier flowering under blue light environments during the nursery period of production. However, there were no detectable differences in fruit yield between SL blue and red light treatment. We did not see accelerated harvests.

In this study, we found that berries from both cultivars had higher SSC in treatments with higher PFD in blue wavelengths (i.e. LB and HB LED treatments for ‘Albion’, and HB for ‘San Andreas’). This result is different from Nadalini et al. (2017), who reported no difference in SSC between separate sole-source red and sole-source blue LED growth chamber treatments. However, Nadalini et al. (2017) did find that the average fruit weight (g) and fruit set (%) was significantly higher under the blue LED light treatment. Similarly, a greenhouse study on frigo strawberries (plants harvested when dormant outdoors and kept in cold storage until needed) also reported increased fruit size in LED treatments of red + blue light, compared to red LED light alone (Samuolienė et al., 2010).

Leaf area and crown numbers were positively affected by all LED treatments (WFR, LB, HB) in ‘San Andreas’ plants during the shortening days of the winter months (Oct. – Dec.). It appears that the SL provided during a typically light-limited time of year allowed for strawberry plants to increase both reproductive and vegetative growth, but to a lesser extent during the lengthening days of spring (Jan. – April). However, other studies have documented that sole-source red lighting increased specific leaf area (SLA) (the ratio of leaf area and dry weight of leaves, $m^2 \cdot kg^{-1}$) when compared to sole-source blue lighting, while sole-source blue lighting increased overall crown weight (Nadalini et al., 2017). Wu et al. (2011) reported similar findings in a growth chamber: combined sole-source lighting of 70% red LED light and 30% blue LED light increased overall crown diameter when compared to traditional T5 fluorescent lighting.

The lengthening days of Experiment 2 elicited limited responses, although stolon production increased with all lighting LED treatments. Differences between cultivars in leaf area and soluble solids content were also seen in during this experiment. Stolon production is typically considered an undesired response due to the partitioning of photosynthetic resources to asexual reproduction of these structures instead of fruit. While stolon removal can be costly, 30% decreases in strawberry yields have been reported when runners are not removed (Hughes et al., 2017). ‘Albion’ is known for producing large amounts of stolons during outdoor and indoor cultivation, while high amounts of stolon production is typically not found with ‘San Andreas’ (UC Davis, n.d.). In this study, ‘San Andreas’ plants produced the lowest stolon weight, while ‘Albion’ plants showed large amounts of runner production throughout Experiment 1. During the lengthening days of

Experiment 2, both cultivars appeared to be more responsive to the SL provided by the LB and HB LED treatments, and both cultivars exhibited increased stolon production. Wu et al. (2011) also reported an increase in stolon production with plants grown under sole-source 70% red LED light and 30% blue LED light in a growth chamber. Although stolons were not removed until the end of each experiment, evaluating differences between cultivar runner production in facilities using CEA techniques could help to alleviate some of the manual labor costs without directly impacting strawberry fruit yields.

Experiments 1 and 2 were run for 2-3 months each, instead of the full 6 months of the off-season period (Oct –April). This allowed us to separate out any seasonal differences and plant responses due to changes in the natural DLI throughout the year. Future studies should evaluate optimum LED DLI on fruit production and yield of strawberry crops and should span the full 6 months of the off-season period. This could allow SS and SL growers to tailor a specific DLI to maximize strawberry yields, and could possibly have implications for production of propagation materials (i.e. stolons).

1.5 Conclusion

LED SL caused a range of response scenarios for the two cultivars of strawberries grown in a greenhouse at two times of year. The most responsive scenario across the two experiments was observed in the 'San Andreas' cultivar during the shortening days in fall (Experiment 1), and using SL of either LB or HB. In that scenario, we noted improvement in overall berry quality (i.e. individual fruit weight, SSC, and overall yield) as well as vegetative growth (leaf area and crown number). Supplemental lighting is a key tool currently being used by CEA growers and researchers alike, and shows potential in increasing off-season high-value crop production. These studies indicate that the addition of supplemental lighting in the form of higher intensities of blue to red wavelengths, during shortening days, improves overall strawberry fruit quality and plant growth.

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