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Improving Winter Growth in the Citrus Nursery with LED and HPS Supplemental Lighting

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***Abstract*. Modern citrus nursery production makes use of potted-tree propagation in greenhouses. Supplemental lighting is one method by which nursery tree growth and profitability may be significantly improved, but limited specific information is available. Five replicated experiments were conducted to determine the utility and effects of increasing daylength during the winter months by supplemental illumination from light-emitting diode (LED) or high-pressure sodium (HPS) lights in citrus nursery propagation. Studies used ‘Valencia’ sweet orange scion, the most common citrus cultivar grown in Florida, and the commercially important rootstocks sour orange, ‘Cleopatra’ mandarin, ‘US-812’, ‘US-897’, ‘US-942’, and ‘US-1516’. Comparisons used the three common types of citrus rootstock propagation: seed, stem cuttings, and micropropagation. Six responses were measured in the lighting experiments, including vegetative growth before budding, scion bud survival, and scion bud growth after budding. Supplemental HPS or LED light to extend daylength to 16 h in the citrus nursery during short-day winter months was observed to be effective in increasing unbudded rootstock liner growth and ‘Valencia’ scion growth on all rootstocks and propagation types. Generally, the positive effect on vegetative growth from an increased daylength was stronger with the HPS light than with LED light, while increasing daylength with LED light, but not HPS light, provided some increased bud growth initiation. Use of HPS or LED supplemental lighting to extend daylength offers significant growth advantage for the citrus nursery industry in winter.**

Nursery propagation is a critical component of citrus production worldwide and usually involves the production of grafted combinations of the desired scion cultivar on a suitable rootstock. To mitigate serious threats from insect and disease problems, modern citrus nursery production in most countries makes use of potted-tree propagation in greenhouses. Under these conditions, there is intense commercial pressure to optimize growth, maintain disease-free and healthy trees, and shorten the time to production of field-ready plants. Citrus nursery practices have been described for practitioners (Aubert and Vullin, 1998; Bremer et al., 2016), and several components of the citrus nursery system have received attention for optimization through research, such as using clean stock (Vidalakis et al., 2010) and nutritional management (Bernardi et al., 2015; Maust and Williamson, 1994). Supplemental light to increase daylength and accelerate plant production is one component of the citrus nursery system that can be important but has received little research attention. Daylength effects on growth of young citrus trees have been described (Piringer et al., 1961; Young, 1961), with pronounced differences between amounts of shoot growth in short daylength and long daylength. Piringer (1961) tested both nucellar seedlings of several *Citrus* species [and *Poncirus trifoliata* (L.) Raf.] and grafted trees of grapefruit/sour orange (*C. paradisi* Macf. on *C. aurantium* L.), finding that longer daylength increased tree growth of all the seedling types and the grafted grapefruit trees and that the growth effect was a combination of more nodes and longer internodes. In another study (Young, 1961), daylength was shown to have no effect on internode length for trees of grapefruit/sour orange, but tree growth was increased 70% by using low-intensity incandescent light to increase daylength. Tree growth was increased 339% when the daylength increase used higher intensity lighting that combined incandescent and fluorescent sources. It was suggested that this indicated both a photoperiod-sensitive and a photosynthetic response. Growth of sweet orange (*C. sinensis* L. Osbeck) on ‘Troyer’ rootstock (*C. sinensis* × *P. trifoliata*) trees was also reported to be increased by extending daylength with incandescent light during the winter (Nauer et al., 1979). Long- and short-day effects were studied on several rootstock selections as seedlings and in graft combination with citrus scions, and results were interpreted as indicating that some rootstocks exhibited a strong positive growth response to long-day treatments, whereas other rootstocks did not (Warner et al., 1979). For ‘Satsuma’ mandarin (*C. reticulata* L. Blanco) on *P. trifoliata* rootstock, both shoot length and shoot fresh weight were significantly larger when plants were grown under 16-h daylength than when plants were grown under 8-h daylength (Inoue, 1989). Research conducted in growth chambers indicated that vegetative growth of two trifoliate hybrid rootstocks may be increased in small potted citrus plants by either long daylength or the use of light to interrupt the dark period during short day periods, suggesting a phytochrome-mediated response (Brar and Spann, 2014). There is evidence that supplemental light increases growth of citrus nursery trees during short days, but there is not clear quantitative information on the amount and nature of the growth improvement among current citrus rootstock types under modern greenhouse conditions and in response to the use of modern supplemental HPS or LED lights.

Supplemental light has been studied in many plant systems and has been shown to typically have large effects to improve or change plant growth. The type, spectra, intensity, and timing of supplemental lighting can each have a large influence on the effects of light on plants (Choong et al., 2018; Craig and Runkle, 2016; Demotes-Mainard et al., 2016; Gomez and Mitchell, 2015; Huché-Thélier et al., 2016; Islam et al., 2012). HPS lamps have been a mainstay of horticultural lighting for many years, and for at least the past decade, LED lights have received considerable attention in horticulture because of their low power use and suitability for targeting particular spectra (Bantis et al., 2018; Hawley et al., 2018; Massa et al., 2008; Xu et al., 2016). Disadvantages of using HPS lighting are the production of radiant heat and their electrical inefficiency combined with a relatively short bulb lifespan, which can increase operation costs (Craver and Lopez, 2016). LED lighting requires an initial high-cost investment but has the advantage of generating minimal heat in addition to the low energy consumption and long life.

Little information is available about the specific effects of daylength, light quality, or light intensity on scion growth in newly grafted or budded trees of tree fruit crops,

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including citrus. The objective of this study was to compare the relative benefits of increasing daylength with industry standard HPS and LED supplemental lighting in the citrus nursery under short-day conditions, including effects on the prebudded rootstock liner and the budded scion. Long-day extension was chosen for our studies, rather than night interruption because the daily light integral during the winter months in the Florida greenhouse is well below the daily light integral of 20 to 25 mol·m^{-2}·d^{-1} (Faust and Logan, 2018) likely required for good growth of citrus nursery crops. This study aimed to evaluate the usefulness of supplemental lighting for several commercially important rootstock clones. Because citrus nurseries are increasingly making use of rootstocks propagated by other methods besides traditional nucellar seedlings (Albrecht et al., 2017), we included a comparison of all three common rootstock propagation types in our study: seedlings, stem cuttings, and tissue culture. The results of these studies can be used to guide practical choices among lighting options available to the billion-dollar citrus nursery industry.

Materials and Methods

Plant material. Six commercially important citrus rootstocks were used in nursery studies: the standard cultivars sour orange (*C. aurantium*) and 'Cleopatra' mandarin (*C. reticulata*), along with four popular hybrid rootstock cultivars developed by U.S. Department of Agriculture (Bowman and Rouse, 2006; Bowman et al., 2016a, 2016b; Bowman and Joubert, 2020): 'US-897' ('Cleopatra' × *P. trifoliata* 'Flying Dragon'), 'US-942' (*C. reticulata* 'Sunki' × 'Flying Dragon'), 'US-812' (*C. reticulata* 'Sunki' × *P. trifoliata* 'Benecke'), and 'US-1516' (*C. maxima* 'African' × *P. trifoliata*). Five experiments were conducted using unbudded rootstocks propagated by seed (Expt. 1) or cuttings (Expt. 2), or budded plants on rootstocks propagated by seed (Expt. 3), cuttings (Expt. 4), or tissue culture (Expt. 5).

Table 1. Natural daylength at the beginning, during, and at the end of the experiments.

Date	Sunrise	Sunset	Daylength (h)
11 Nov. 2018	0732 HR	1838 HR	11.1
21 Dec. 2018	0707 HR	1732 HR	10.4
9 May 2019	0637 HR	2000 HR	13.4

For Expts. 1 and 3, uniform nucellar seedlings were grown from certified seed source trees located at the Whitmore Foundation Farm (Groveland, FL) for the respective rootstocks. These seed were harvested from the source trees in the previous season, treated with 8-hydroxyquinoline sulfate, and stored at 4 °C until use.

For Expts. 2 and 4, single-node stem cuttings were propagated from selected 1-year-old uniform nucellar seedlings of the respective rootstocks growing in the greenhouse. Methods for rooting of the cuttings on the mist bench were as previously described (Bowman and Albrecht, 2017).

For Expt. 5, rootstock liners that had been propagated by tissue culture were obtained from a commercial micropropagation facility (Agromillora, Wildwood, FL). Source plant material used to establish the sterile tissue culture sources of the respective rootstocks were obtained from certified clean sources at Florida Department of Agriculture and Consumer Services-DPI (FDACS-DPI, Winter Haven, FL).

For budded Expts. 3, 4, and 5, seedlings, cuttings, or micropropagated liners of the rootstocks were budded with the certified sweet orange (*C. sinensis*) scion clone 'Valencia' 1-14-19, obtained from FDACS-DPI. Grafting of the 'Valencia' scion onto the rootstock liner was by inverted T bud, and grafted buds were wrapped with budding tape for 2 weeks. One week after unwrapping the buds, the rootstock was trimmed and looped to force bud growth, using methods as previously described (Bowman, 1999).

Table 2. Start and end of experiments and light treatments.

Expt.	Rootstock type	Start	End
1	Seedlings	4 Dec. 2018	29 Jan. 2019
2	Cuttings	4 Dec. 2018	29 Jan. 2019
3	Seedlings	31 Jan. 2019^{z}	9 May 2019
4	Cuttings	31 Jan. 2019^{z}	9 May 2019
5	Micropropagations	1 Nov. 2018^{z}	7 Feb. 2019

^{z}Budding date.

Table 3. Maximum photosynthetic photon flux density (*PPFD*) and power use of lighting treatments in the greenhouse.

	No added light, noon	No added light, pre-daylight	LED, pre-daylight	HPS, pre-daylight
PPFD (μmol·m^{-2}·s^{-1})				
400–700 nm	1120 ± 102	0.88 ± 0.25	92.7 ± 5.94	306.5 ± 21.2
380–780 nm	1473 ± 138	1.29 ± 0.23	95.3 ± 6.13	339.3 ± 25.4
Power use^{z}				
Voltage	NA	NA	114.1 ± 1.42	112.8 ± 0.66
Amperage	NA	NA	2.6 ± 0.02	9.3 ± 0.06
Power	NA	NA	302.2 ± 0.84	1049.2 ± 6.61

^{z}Volts, amps, and watts were as measured for light fixture(s) and associated timer that provided coverage for 2.5 m^{2} unit bench space.

HPS = high-pressure sodium; LED = light-emitting diode; NA = not applicable.

Growing conditions. Seedlings and stem cuttings were started in soilless potting mix (Pro Mix BX; Premier Horticulture, Inc., Quakertown, PA), using racks of 3.8 cm × 21 cm cone cells (Cone-tainers; Stuewe and Sons, Tangent, OR). Micropropagated plants were initially growing in 3.8 × 4.4 cm paper pots (Ellepots) containing a mix of peat and coconut fiber (Albrecht et al., 2017). All plants were transplanted into 2.54-L pots (Treepots; Stuewe and Sons, Tangent, OR) using the soilless potting mix (Pro Mix BX) at least 8 weeks before start of the experimentation.

The plants received a liquid fertilizer application of water-soluble fertilizer (20N–10P–20K; Peters Professional, The Scotts Company, Marysville, OH) every other week, at a rate of 400 mg N/L. Between fertilizer applications, plants were irrigated with water as needed. Insecticides and miticides were also applied as needed.

Throughout the experiments, the plants were grown in a temperature-controlled greenhouse with a mean weekly temperature of 26.5 to 29.7 °C. During the experiments, average weekly minimum and maximum temperatures were 24.6 and 32.4 °C, respectively. Circulating fans provided continuous air movement in the area between the plant canopy and the lights to help minimize local heat effects generated by the light source.

Illumination treatments. The two light sources used were 1000-W high-pressure sodium fixture with digital ballast (Growbright, HGT Supply, Melbourne, FL), and 150-W LED lightbar (XC150 vegetative spectrum, Kind Grow Lights, Santa Rosa, CA). All five experiments were conducted in a greenhouse divided into 15 randomized bench areas. Five replications-bench areas had no supplemental light, five replications had extended daylength using LED light, and five replications had extended daylength using HPS light. Greenhouse bench spaces were set up so that each replication occupied an area of about 1.1 m × 2.3 m (or 2.5 m^{2} unit) bench space, and plants included in each replication were centered under the defined lighted or unlighted area. Preliminary measurements with a light meter indicated that one HPS fixture or two LED fixtures were needed to provide uniform light over the 2.5 m^{2} unit bench space at the height described below. Five replicates were used for each treatment combination, with each replicate consisting of 20 to 30 plants and a total of 325 to 460 plants per experiment.

For the treatments with supplemental light, LED and HPS lights were positioned at 150 cm above the greenhouse benchtop, which was 125 cm above the top of the 2.54-L pot and ≈110 cm above the height at which the 'Valencia' bud was inserted in the budded plants. This distance was maximized to reduce potential effects from heat emission of the HPS light source.

The supplemental light treatments were designed to increase the daylength to ≈16 to 17 h during the testing period from 1 Nov. 2018 to 9 May 2019. The natural daylength during this time period ranged from 10.4 to 13.4 h (Table 1). From 1 Nov. 2018 until 26 Feb. 2019, the supplemental HPS and LED lighting was on from 0130 to 0830 HR, giving an effective daylength of 16.0–17.1 h. Beginning on 26 February, the supplemental lighting was on from 0230 to 0830 HR, giving an effective daylength of 15.9 to 17.5 h. The start and end of the light treatments for all experiments are listed in Table 2.

Data collection and analysis. To define radiation conditions, light energy was measured using a Spectrometer (UPRtek PG100N, Zhunan, Taiwan) for each replication at 110 cm below LED and HPS lights, or equivalent location for nonlighted treatment at 0200 HR on a moonless night. All lights in the experimental area were on during the light measurement readings, so that artificial light from illuminated areas to unlighted areas was included in measurements. Light energy was measured at those same locations in the greenhouse at noon during a cloudless day in Apr. 2019, and without any supplemental light. The maximum photosynthetic photon flux density (*PPFD*, 400–700 nm) at midday outside the greenhouse was 1860 $\mu mol\cdot m^{-2}\cdot s^{-1}$. In the greenhouse testing area, *PPFD* at noon was 1120 $\mu mol\cdot m^{-2}\cdot s^{-1}$ (Table 3), or ≈60% of PPFD energy available outside the greenhouse. The HPS and LED treatments supplied 306.5 and 92.7 $\mu mol\cdot m^{-2}\cdot s^{-1}$ *PPFD* to the treatment areas, respectively, during the predawn morning hours, which was 27% and 8% of the PPFD available in the experimental area at midday. Light energy supplied by the HPS treatment greatly exceeded the total energy supplied by the LED treatment through most parts of the spectra, except for blue light (400–500 nm), where the LED treatment had energy values about 2.7 times those of the HPS treatment. A visual representation of light spectra from the different treatments is provided in Fig. 1.

Electrical energy (volts, amps, watts) used by the treatments was measured for each of the ten illuminated areas at least 15 min after the lights were on (Table 3). This measurement included one HPS fixture and one timer per HPS area, and two LED units and one timer per LED area.

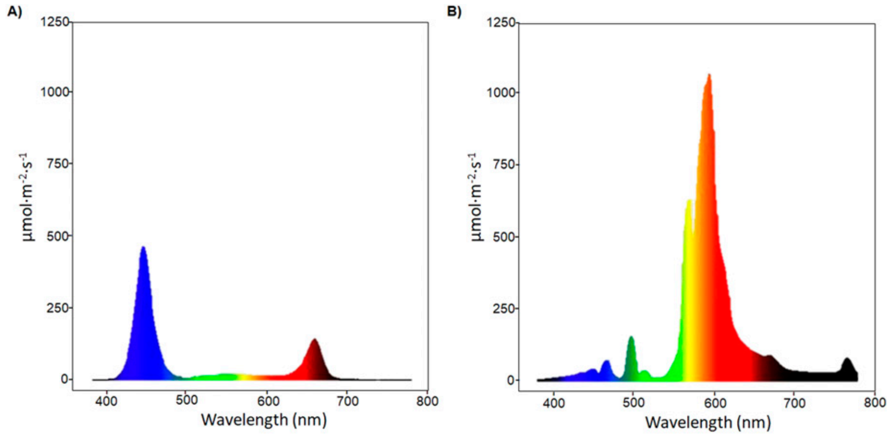

Fig. 1. Graphical spectra during predawn hours at 110 cm below the light fixtures for the (**A**) the LED and (**B**) HPS light treatments.

In the unbudded seedling and cutting experiment, plant stem diameters were measured at 5 cm above the soil at the start of the experiment and at the end of the experiment 8 weeks later. Values were converted to trunk cross sectional area (TCSA) and expressed as percent increase in TCSA from time 0 to 8 weeks for data analysis.

In budded Expts. 3 through 5, plants were scored for bud survival and bud growth initiation (shoot tip of bud at least 2 mm long) at 5 and 14 weeks after budding (wab); values were converted to percent of total plants budded or plants surviving for data analysis. In the budded experiments, plants with growing 'Valencia' scions at least 10 cm long were measured at 14 wab for TCSA at 5 cm above graft union and for average internode length using only nodes with fully expanded leaves.

Data were analyzed using Statistica 10 software (Dell Statistica, Tulsa, OK). Comparison of light effects for a single rootstock within an experiment was by one-way analysis of variance (ANOVA). Factorial ANOVA was employed within experiments, using light-type and clone (or rootstock) as the independent variables. Mean separation of the light-type treatments for significant ANOVA results with $P < 0.05$ were by Tukey's test at $\alpha = 0.05$.

Table 4. Unbudded seedling and cutting growth (0–8 weeks) as measured by trunk cross-sectional area (TCSA) increase (%).

	Sour orange	Cleopatra	US-897	US-942	US-812	All
Seedlings (Expt. 1)						
Seedling initial TCSA[z]	7.5 ± 4.7	8.1 ± 3.1	8.2 ± 4.1	16.0 ± 5.5	15.6 ± 5.4	—
Seedling TCSA increase						
HPS	299 a	199 a	201 a	149 a	118	198 a
LED	256 ab	178 ab	151 b	143 a	116	175 a
None	199 b	138 b	137 b	107 b	95	138 b
P > F, L	0.017	0.002	0.003	0.002	0.217	<0.001
P > F, C						<0.001
P > F, L × C						0.422
Cuttings (Expt. 2)						
Cutting initial TCSA	—	—	8.3 ± 1.8	8.5 ± 2.2	7.6 ± 1.7	—
Cutting TCSA increase						
HPS	—	—	154 a	161 a	192 a	169 a
LED	—	—	132 a	152 a	185 a	156 a
None	—	—	103 b	108 b	132 b	114 b
P > F, L	—	—	<0.001	<0.001	<0.001	<0.001
P > F, C						<0.001
P > F, L × C						0.661

[z] Initial TCSA values stated are means (millimeters) ± SD.

Mean groups for significant analysis of variance within columns by experiment were by Tukey's test at $P < 0.05$.

C = clone; HPS = high-pressure sodium; L = light; LED = light-emitting diode.

Results

TCSA and unbudded liners. Seedling rootstock liners exposed to day-length extension had significantly more growth (TCSA) compared with natural lighting in winter nursery conditions whether the daylength extension was through HPS or LED lighting (Table 4). There were significant rootstock clone effects among the seedlings, but large differences in initial seedling size by rootstock may have contributed to these effects. Regardless of seedling starting size, a positive effect on liner TCSA growth from the extended daylength was common to all the seedling rootstock clones. Overall, the increase in seedling liner TCSA over the 8 weeks was 138% for natural light treatment, 175% for LED day-length extension, and 198% for HPS day-length extension. The TCSA growth improvement from HPS daylength extension was significantly greater than that provided by LED daylength extension for one of the seedling rootstock clones ('US-897'). A similar beneficial effect from daylength extension was observed on growth of rootstock liners propagated by stem cuttings, with all three rootstock clones showing a significant improvement in TCSA growth from both light treatments. The overall increase in cutting liner TCSA was not significantly larger for HPS as compared with LED lighting, and the increase in cutting liner TCSA over the 8 weeks was 114% for natural light treatment, 156% for LED daylength extension, and 169% for HPS daylength extension. No interaction was observed for light treatment and clone for the increase in TSCA.

Table 5. Valencia scion bud survival (%) at 5 weeks after budding.

	Sour orange	Cleopatra	US-897	US-942	US-812	US-1516	All
Seedlings (Expt. 3)							
HPS	100	84	100	72	100	—	91
LED	100	92	93	72	87	—	89
None	92	80	100	52	73	—	79
P > F, L	0.110	0.679	0.397	0.423	0.104	—	0.060
P > F, R							<0.000
P > F, L × R							0.656
Cuttings (Expt. 4)							
HPS	—	—	82	77	90	—	83
LED	—	—	77	87	95	—	87
None	—	—	67	70	82	—	73
P > F, L	—	—	0.508	0.581	0.397	—	0.199
P > F, R							0.186
P > F, L × R							0.948
Micropropagations (Expt. 5)							
HPS	—	—	100	78	100	100	94
LED	—	—	98	78	100	100	94
None	—	—	100	98	97	95	97
P > F, L	—	—	0.397	0.568	0.397	0.110	0.770
P > F, R							0.051
P > F, L × R							0.612

HPS = high-pressure sodium; L = light; LED = light-emitting diode; R = rootstock.

Table 6. Percentage of 'Valencia' scion buds growing at 5 weeks after budding.

	Sour orange	Cleopatra	US-897	US-942	US-812	US-1516	All
Seedlings (Expt. 3)							
HPS	52	96	38	73	35	—	59
LED	72	81	65	55	35	—	62
None	72	59	40	78	27	—	55
P > F, L	0.453	0.126	0.382	0.427	0.837	—	0.712
P > F, R							<0.001
P > F, L × R							0.268
Cuttings (Expt. 4)							
HPS	—	—	42	29	10	—	27
LED	—	—	58	26	3	—	29
None	—	—	29	47	22	—	32
P > F, L	—	—	0.281	0.558	0.104		0.853
P > F, R							0.006
P > F, L × R							0.199
Micropropagations (Expt. 5)							
HPS	—	—	45	27	11	2	21
LED	—	—	32	22	14	5	19
None	—	—	31	5	6	2	11
P > F, L	—	—	0.480	0.228	0.449	0.712	0.086
P > F, R							<0.001
P > F, L × R							0.620

HPS = high-pressure sodium; L = light; LED = light-emitting diode; R = rootstock.

Table 7. 'Valencia' scion buds growing (%) at 14 weeks after budding.

	Sour orange	Cleopatra	US-897	US-942	US-812	US-1516	All
Seedlings (Expt. 3)							
HPS	80	100	77	87	55	—	80 b
LED	96	100	93	96	90	—	95 a
None	92	100	58	93	77	—	84 ab
P > F, L	0.308	nd	0.090	0.621	0.126	—	0.012
P > F, R							<0.001
P > F, L × R							0.169
Cuttings (Expt. 4)							
HPS	—	—	90	86	61	—	79
LED	—	—	100	80	70	—	83
None	—	—	94	82	59	—	78
P > F, L	—	—	0.128	0.845	0.350	—	0.505
P > F, R							<0.001
P > F, L × R							0.551
Micropropagations (Expt. 5)							
HPS	—	—	76	47	24	8	38
LED	—	—	83	68	37	16	51
None	—	—	67	28	23	2	30
P > F, L	—	—	0.387	0.054	0.560	0.082	0.004
P > F, R							<0.001
P > F, L × R							0.694

Mean groups for significant analysis of variance within columns by experiment were by Tukey's test at $P < 0.05$. nd = not determined; HPS = high-pressure sodium; L = light; LED = light-emitting diode; R = rootstock.

Bud survival and growth of budded plants at 5 wab. Comparison of 'Valencia' bud survival among the light treatments for each of the rootstocks in each of the three experiments found no significant effect of the daylength extension on bud survival, although a trend ($P = 0.060$) was observed in the seedling experiment where the highest survival was measured with HPS lighting (Table 5). Rootstock clone had a significant effect on 'Valencia' bud survival in the seedling experiment, and a similar trend ($P = 0.051$) was observed in the micropropagation experiment. No interaction was observed between light treatment and rootstock clone for this trait.

No significant effect of daylength extension on early bud growth was observed for any of the rootstock clones in the three experiments (Table 6). In contrast, rootstock clone had a significant effect on 'Valencia' bud early growth in all three experiments. No interaction for light treatment and rootstock was observed for this trait.

Percent of budded plants growing at 14 wab. Comparison of the percent of 'Valencia' buds growing at 14 wab did not demonstrate significant differences for individual rootstocks within any of the three experiments (Table 7). However, when rootstocks within each experiment are combined in the analysis, Expts. 3 and 5 both indicate a significant effect from light treatment. In the budded plant experiments with seedlings and micropropagations, daylength extension with LED light increased the percentage of 'Valencia' buds that were growing at 14 wab by 10% to 20% compared with natural lighting and daylength extension using HPS. Rootstock clone had a significant effect on percent of scion buds growing at 14 wab in all three experiments. No interaction was observed for light treatment and rootstock.

'Valencia' scion shoot TCSA. Daylength extension had at significant effect on 'Valencia' shoot TCSA at 14 wab in all three experiments (Table 8). Both HPS and LED daylength extension produced larger shoot TCSA at 14 wab in two of the seedling rootstocks (Expt. 3) compared with the unlighted control. The beneficial effect on TCSA from HPS was more pronounced than the effect from LED, with HPS lighting producing a significantly larger TCSA across most of the rootstocks in all three experiments. Rootstock clone had a significant effect on TCSA at 14 wab in Expts. 3 and 4. No interaction was observed for light treatment and rootstock.

'Valencia' shoot internode length. Day length extension with HPS or LED had no significant effect on 'Valencia' shoot internode length for most of the rootstocks in the three experiments (Table 9). For only the 'Valencia' shoots on 'US-897' rootstock from Expt. 5, significantly longer internodes were measured when plants were supplemented with HPS compared with the natural lighting. Rootstock clone had a significant effect on internode length in Expt. 3, and a similar trend was observed in experiment 4 (P = 0.060). No interaction was observed for light treatment and rootstock.

Table 8. 'Valencia' scion shoot trunk cross sectional area (mm^2) on rootstocks at 14 weeks after budding.

	Sour orange	Cleopatra	US-897	US-942	US-812	US-1516	All
Seedlings (Expt. 3)							
HPS	18.6	13.0 a	7.2 a	9.9 a	10.2	—	12.7 a
LED	15.6	11.8 a	5.9 a	7.7 ab	7.0	—	10.7 ab
None	15.7	9.0 b	4.4 b	6.9 b	6.2	—	9.8 b
P > F, L	0.126	0.002	<0.001	0.033	0.039	—	<0.001
P > F, R							<0.001
P > F, L × R							0.850
Cuttings (Expt. 4)							
HPS	—	—	7.8 a	9.3	9.5	—	8.6 a
LED	—	—	6.0 b	9.2	7.9	—	7.4 b
None	—	—	5.6 b	7.5	6.8	—	6.5 b
P > F, L	—	—	0.003	0.116	0.069	—	<0.001
P > F, R							<0.001
P > F, L × R							0.586
Micropropagations (Expt. 5)							
HPS	—	—	7.6 a	8.7 a	7.1	6.1	7.7
LED	—	—	5.9 b	6.9 ab	5.6	5.9	6.1
None	—	—	5.5 b	3.9 b	7.2	7.7	5.6
P > F, L	—	—	<0.001	0.018	0.494	0.695	0.078
P > F, R							0.947
P > F, L × R							0.120

Mean groups for significant ANOVA within columns by experiment were by Tukey's test at $P < 0.05$.
HPS = high-pressure sodium; L = light; LED = light-emitting diode; R = rootstock.

Table 9. 'Valencia' scion shoot internode length (mm) on rootstocks at 14 weeks after budding.

	Sour orange	Cleopatra	US-897	US-942	US-812	US-1516	All
Seedlings (Expt. 3)							
HPS	19.1	18.4	14.6	16.3	17.5	—	17.5
LED	19.8	19.1	16.3	15.8	15.3	—	17.9
None	19.8	18.4	14.8	16.6	17.6	—	17.9
P > F, L	0.574	0.366	0.122	0.594	0.083	—	0.824
P > F, R							<0.001
P > F, L × R							0.103
Cuttings (Expt. 4)							
HPS	—	—	15.2	16.1	14.4	—	15.3
LED	—	—	14.8	15.7	14.4	—	14.9
None	—	—	15.2	16.2	16.2	—	15.8
P > F, L	—	—	0.690	0.802	0.392	—	0.191
P > F, R							0.062
P > F, L × R							0.693
Micropropagations (Expt. 5)							
HPS	—	—	17.3 a	16.6	16.3	16.6	16.9
LED	—	—	16.2 ab	17.3	16.0	16.4	16.4
None	—	—	15.1 b	16.2	15.9	15.4	15.5
P > F, L	—	—	0.018	0.522	0.850	0.602	0.354
P > F, R							0.810
P > F, L × R							0.549

Mean groups for significant analysis of variance within columns by experiment were by Tukey's test at $P < 0.05$.
HPS = high-pressure sodium; L = light; LED = light-emitting diode; R = rootstock.

Discussion

The results from this study demonstrate that daylength extension with supplemental light in the citrus nursery is beneficial to increase vegetative growth, as measured by stem diameter increase, of both the unbudded rootstock liner and the young budded plant during the short days of winter. This effect was similar for a wide diversity of rootstock cultivars and regardless of whether the rootstock liner was propagated by nucellar seed, stem cuttings, or tissue culture. The increase in vegetative growth was largest when the daylength extension was provided by HPS lighting, although in most cases, LED lighting also significantly increased growth compared with the controls receiving only natural light. The larger growth response under the HPS may be associated with its more than 3× higher *PPFD* compared with the LED light source used in this study, although the growth differential was relatively small compared with the large difference in *PPFD* between the lights. It is also possible that, despite constant air movement over the plants and ample distance between plants and light source, the higher heat produced by the HPS lighting may have contributed somewhat to the HPS growth advantage. Whether the relatively small growth advantage from HPS lighting was enough to justify the much higher power usage and shorter bulb life compared with the LED lighting would need to be assessed by the situation at individual citrus nurseries.

For the budded nursery plants, there was no evidence that the daylength extension affected bud survival or initiation of bud growth at 5 wab. However, in some cases, daylength extension with LED lighting resulted in an increase in initiation of bud growth at 14 wab. This increase in bud initiation from LED lighting may be a photomorphogenic response, although it does not appear to be the result of a typical shade-avoidance triggered by low red to far-red ratio (Park and Runkle, 2018) because the LED lighting had a high red to far-red ratio. Bud outgrowth has been noted to be regulated by red and far-red light, but responses differ by species (Demotes-Mainard et al., 2016), and this has not been studied in citrus. Full understanding of this effect in citrus, and the opportunity to make larger improvements in budbreak (bud outgrowth) with light spectrum manipulation, will need to await further study. Taken together, the spectrum and *PPFD* of the LED lighting was superior to HPS lighting at inducing the start of bud growth, but once bud growth began, the higher *PPFD* HPS lighting was superior to increase resulting shoot growth.

This is the first study to describe the effects of using supplemental HPS and LED lighting to extend daylength in the winter citrus nursery, or in the nursery of any grafted tree crop. Because there is tremendous pressure to improve profitability in the greenhouse nursery through increased plant growth, taking advantage of long-lived and power-efficient LED lighting optimized for plant growth should provide improved opportunities for success. Although HPS lighting was superior to LED lighting for many of the measured variables, this advantage was generally small, and optimization of LED lighting for spectral composition and total daily light intensity may result in further improvement of plant production. Night interruption in combination with increased far-red illumination may be another strategy to increase bud burst while also accelerating shoot growth. The superiority of HPS lighting for many of the growth parameters may be associated with the more than 3-fold higher energy in the far-red spectrum in addition to an increased temperature compared with the LED lights used in this study.

Although this study focused on examining the effects of daylength extension on the growth of unbudded and budded plants, in most cases, there were significant effects of rootstock clone on the metric of measurement being examined. This corresponds with significant differences in the rate of nursery growth for different citrus rootstock seedlings and success of budded plants on different rootstocks that have been previously documented (Bowman and Rouse, 2006; Bowman et al., 2016a). Four of the rootstocks used in this study were hybrids of trifoliate orange, a deciduous species, which undergoes dormancy during the winter months. Therefore, differences in the response to supplemental lighting may be associated with the varying influences of the dormancy trait conferred by trifoliate orange among the different rootstocks. However, differences in the average rootstock plant size at the beginning of the light treatments likely also played a role in the different responses. The value of using several rootstocks in this study was to indicate the applicability for the daylength effects to a wide range of rootstocks.

Our results also suggest some differences in relative growth and success of budding on rootstock liners among the three propagation methods: seed, stem cuttings, and tissue culture. However, because the experiments were not designed to compare propagation methods, we think it is not appropriate to infer meaningful comparisons between propagation types from these results. The value of using three propagation types was to evaluate the applicability for the daylength effects to different propagation types, and the results clearly suggest that daylength extension will benefit growth of trees regardless of rootstock propagation method.

The results from this study confirmed previous reports (Inoue, 1989; Nauer et al., 1979; Piringer et al., 1961; Warner et al., 1979; Young, 1961) of beneficial effects from artificial lighting to extend daylength in the citrus nursery during periods of short natural daylength. This study expanded on those previous observations and demonstrated the usefulness of the methods as applied to citrus rootstocks of current importance, all three types of citrus rootstock propagation employed in the modern citrus nursery, and as implemented with modern HPS or LED lighting. Relative growth benefit from daylength extension with supplemental lighting, although significant, was observed to be much smaller than in those earlier reports. As measured by TCSA over 8 weeks in unbudded liners, growth improvement was 27% to 37% when using LEDs for daylength extension, and 43% to 48% when using HPS. We speculate that those earlier studies were conducted in greenhouses with more limited natural lighting (less transfer of natural sunlight) than used in the present study. Contrary to the report by Warner et al. (1979), we observed this beneficial effect to be similar across a broad range of citrus rootstock clones. As was noted in one previous study (Young, 1961), we observed that increased plant growth resulting from longer daylength was often significantly affected by the quality or intensity of the supplemental light. In relation to a previous report that daylength extension with artificial light resulted in increased internode length (Piringer et al., 1961), we observed that daylength extension had a significant effect on internode length of budded plants only for the combination of HPS light and one rootstock, and this effect was relatively small and probably of little economic importance. Although we did not evaluate the effects of night interruption for a phytochrome-mediated response as was previously described (Brar and Spann, 2014), the significant increases in growth induced by HPS and LED light sources at very different *PPFD*s in our study suggest that at least some of the observed beneficial effects from daylength extension were not a phytochrome-mediated response but the result of increased or improved photosynthesis, as proposed by Young (1961).

In conclusion, supplemental HPS or LED light to extend daylength to 16 h in the citrus nursery during short-day winter months was effective in increasing both unbudded rootstock liner growth and 'Valencia' scion growth on several citrus rootstocks, regardless of rootstock propagation type. Generally, the positive effect on vegetative growth from an increased daylength was stronger with the higher intensity HPS light than with LED light, whereas increasing daylength with LED light provided some increased bud growth initiation, which was not observed with the HPS light treatment. Relative growth improvement resulting from the daylength extension was 27% to 48% over an 8-week period. For the particular HPS and LED light systems used in this study, the HPS lighting had a much lower initial cost but much higher power use compared with the LED lighting covering a similar greenhouse area. The expected life of the LED units is reported to be much longer than that of the HPS units. Therefore, LED provides a more cost-effective option for increasing citrus nursery production in the longer term. The use of supplemental HPS or LED light in the winter citrus nursery appears useful to improve plant growth, but additional study for refinement of spectra, intensity, and duration of light treatment may provide further improvements.

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