INFLUENCE OF DAILY LIGHT INTEGRAL, LIGHT QUALITY, AND ROOT-ZONE TEMPERATURE ON YOUNG PLANT PRODUCTION

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ABSTRACT

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Young ornamental plants and herbs are propagated from seeds and unrooted cuttings in greenhouses. Previous research has determined that the photosynthetic daily light integral (DLI) and air average daily temperature (ADT) set point should be ~10 mol·m^{-2}·d^{-1} and ~24 °C, respectively, for most ornamental plants. However, young plant recommendations are lacking for air ADT and root-zone heating (RZH) set points for cold-tolerant crops, appropriate DLIs for herbs, and the minimum duration of far-red (FR) radiation needed during the seedling stage to induce long-day plants (LDPs) into flower. Therefore, our objectives were to 1) determine if cold-tolerant crops can be rooted at a lower air ADT with RZH, 2) quantify how DLI influences rooting of herb cuttings, and 3) determine the minimum duration of supplemental lighting (SL) providing FR radiation during seedling production to hasten subsequent time to flower of LDPs. High-quality calibrachoa, nemesia, nepeta, and osteospermum rooted cuttings were produced at an air ADT and RZH temperature of 16 and 24 °C, respectively, while campanula, petunia, and phlox were successfully propagated at an air ADT and RZH set points of 16 and 21 °C and 21 and 27 °C, respectively. A DLI of 10 to 12 mol·m^{-2}·d^{-1} produced high-quality liners of oregano, rosemary, sage, spearmint, and thyme. Seedlings of calibrachoa, petunia, and snapdragon were taller when grown under FR SL for ≥14 d and subsequent flowering was hastened by 3 to 8 d under FR SL for 28 to 35 d compared to seedlings under high-pressure sodium lamps for 28 to 35 d. These results provide further insight for greenhouse growers that want to produce high-quality liners and seedlings without sacrificing finish plant quality.

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Introduction

As of 2018, production of annual and perennial ornamental plants in the United States (U.S.) takes place under 80 million m^2 of cover, with 49% of the space allocated to greenhouse production (USDA, 2019). Greenhouse production is advantageous because plants can be produced year-round as environmental parameters such as light and temperature can be controlled to manipulate plant growth and development. During winter months, greenhouse production of plants produced from seed (plugs) or vegetative cuttings (liners) is at its peak. The production of young plants is the basis for producing flats, hanging baskets, and potted finished plants for the spring market. Additionally, young plant production has seen a 14% increase from 2008 to 2018, with a total value of propagative annual bedding and herbaceous perennial plant material of U.S. $313 million in 2018 (USDA, 2009, 2019).

The goal of commercial greenhouse growers is to produce high-quality plugs and liners, which are typically compact and fully rooted, and have a large stem caliper and a high root dry mass (Currey et al., 2012; Randall and Lopez, 2014). Due to young plant production coinciding with winter months, outdoor environmental parameters such as radiation intensity as well as temperature can be unconducive for plant growth. However, manipulation of the greenhouse environment can elicit a positive response in plant growth and development to produce a high-quality young plant. Additional radiative energy via supplemental lighting (SL) provided by high-pressure sodium (HPS) lamps or light emitting-diode (LED) fixtures increases biomass accumulation and overall plant quality in relation to no additional SL (Currey and Lopez, 2013; Hurt et al., 2019; Randall and Lopez, 2014). Furthermore, spectral qualities in the waveband of 380 to 780 nm influence plant morphology through photoreceptors (Thomas and Vince-Prue, 1997). Plant temperature, driven by surrounding air and root-zone temperatures, can lead to increases in shoot and root development, respectively (Blanchard and Runkle, 2011; Blanchard et al., 2006).

Propagation of Herbaceous Plants

Herbaceous cutting propagation

For horticultural purposes, plants are propagated either sexually via seeds or asexually via bulbs, corms, roots, grafts, and cuttings of stems or leaves. Asexual propagation is used in place of sexual propagation when seed propagation is costly or is ineffective (Dole and Hamrick, 2006). It also allows growers to produce true-to-type plants from the mother plant. In the greenhouse industry, 55% of the top floriculture crops are propagated by herbaceous shoot-tip cuttings making this the most common asexual method of propagation (Dole and Hamrick, 2006).

There are five stages of vegetative unrooted cutting propagation: 0) preparation prior to arrival; 1) arrival and sticking; 2) callusing; 3) root development; and 4) toning (Klopmeyer et al., 2011). Before the arrival of cuttings (Stage 0), proper sanitation as well as tray size and soilless medium need to be considered in preparation for receiving the cuttings (Klopmeyer et al., 2011). Upon arrival of cuttings (Stage 1), they need to be inspected for any damage and either inserted into a soilless medium immediately or placed in a storage room with an air temperature of 10 °C and relative humidity of at least 60% to 70% for a short period of time before planting to prevent wilting and desiccation (Klopmeyer et al., 2011).

Various types and sizes of stem cuttings are harvested from stock plants based on plant species, size of the parent plant, and desired crop timing. Terminal shoot-tip cuttings are made up of the stem apex, young leaves, and at least one mature leaf (Dole and Hamrick, 2006). Basal cuttings are taken from the crown of the plant and can include stem tissue and un-elongated crown tissue. Subterminal cuttings are those with at least one axillary bud and leaf but without a terminal apex. For optimal results with subterminal cutting, the stem and bud must be placed below the substrate surface (Dole and Hamrick, 2006).

Once an unrooted cutting is inserted into a soilless medium, the photosynthetic daily light integral (DLI) should be low, between 3 to 5 $mol \cdot m^{-2} \cdot d^{-1}$ [a photosynthetic photon flux density (*PPFD*) of 90 to 120 $\mu mol \cdot m^{-2} \cdot s^{-1}$], to prevent water loss and plant stress, with a 16-h photoperiod (Hartmann et al., 2011; Lopez et al., 2017). After the first few days of propagation, the process of callusing (Stage 2) the initial process of cell dedifferentiation, begins (Hartmann et al., 2011). Dedifferentiation is the ability of previously differentiated cells to form a new meristematic growing region via cell division. Callus presence does not directly correlate to rooting but is a positive signal that cutting cells are dedifferentiating and will likely develop roots (Dole and Hamrick, 2006). For callusing, the recommended substrate temperature is between 18 to 25 °C with day air temperatures of 21 to 27 °C and 15 °C at night for temperate species (Hartmann et al., 2011). Relative humidity should be 75% to 90% and warm water (29 to 32 °C) should be used in the mist lines (Dole and Hamrick, 2006). Additionally, the DLI can gradually increase from 3 to 8 $mol \cdot m^{-2} \cdot d^{-1}$ (*PPFD* between 120 to 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$) during the callusing stage (Lopez et al., 2017). Once 50% of the cuttings begin differentiating root initials, the environmental conditions can be further manipulated to support the development of adventitious roots (Stage 3) (Dole and Hamrick, 2006).

The first step in root generation is to replace the outer injured cells with suberin to protect the wound from pathogens and desiccation (Hartmann et al., 2011). Next, the living cells within the plant divide and produce parenchyma cells, which forms a callus, and later a periderm (Hartmann et al., 2011). Lastly, the cells in proximity to the vascular and phloem tissue divide and produce the adventitious roots (*de novo*) (Hartmann et al., 2011). The *de novo* adventitious root formation occurs with 1) dedifferentiation of cells, 2) formation of root initials via meristematic vascular tissue, 3) root initials organized into root primordia and 4) emergence of the root primordia and creation of vascular tissue between the primordia and cutting (Hartmann et al., 2011).

As roots form, the substrate temperature can be reduced to between 19 to 21 °C and the night air temperature can increase to 16 to 20 °C, while keeping the day air temperature the same as previous. Media moisture should also be reduced at this time by extending the intervals between misting while still maintaining a high relative humidity (Dole and Hamrick, 2006). After roots emerge and develop, the DLI and *PPFD* can increase to 6 to 8 $mol \cdot m^{-2} \cdot d^{-1}$ and 200 to 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively (Lopez and Runkle, 2008; Torres and Lopez, 2011).

Once a root ball forms, the cutting can be toned (Stage 4) for shipping and transplanting (Dole and Hamrick, 2006). To tone a cutting, misting and relative humidity needs to be significantly reduced and light intensity should increase to a DLI of at least 10 $mol \cdot m^{-2} \cdot d^{-1}$ (*PPFD* of 400 to 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$) (Lopez et al., 2017). The night air temperature should decline to 16 to 18 °C but the day air and substrate temperature can be maintained as previous (Dole and Hamrick, 2006).

Plug production

Sexual propagation or the use of seed for replicating plant material must be subjected to favorable conditions for germination to occur. Seedling production is divided into four stages: 1) seed sow and radicle emergence; 2) hypocotyl and cotyledon emergence and root establishment;

3) growth and development of true leaves; and 4) growth until a plant is considered ready for transplanting (Hartmann et al., 2011; Styer, 2011). Seed germination takes place during Stages 1 and 2 and is highly dependent on the microenvironment the seed is exposed to. To provide adequate germination conditions for most crops, the seed should be covered with a thin layer of soilless media or vermiculite. This will aid in providing the right moisture, air temperature, and humidity around the seed as well as expose the seed to darkness, which supports proper root emergence (Styer, 2011).

During the first stage of plug production, substrate temperatures should be as warm as 25 °C for cold-sensitive crops and as low as 19 to 16 °C for cold-tolerant crops to promote uniform germination (Styer, 2011). Light is typically not necessary for the first stage of germination and should remain below a *PPFD* of 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Lopez et al., 2017). However, some crops require light for germination, including begonia (*Begonia* spp.), gerbera (*Gerbera jamesonii*), impatiens (*Impatiens* spp.), petunia (*Petunia ×hybrida*), primula (*Primula* spp.), and snapdragon (*Antirrhinum majus*) (Styer, 2011). Moisture is also highly important during the first two stages of germination as too much or not enough moisture can result in poor germination percentage (Styer, 2011). Fine-mist nozzles can be used to provide enough water to the seed, but not so much as to displace it (Styer, 2011). When phasing from Stage 1 to 2, the water content in the media should be reduced (Hartmann et al., 2011). Once germination is complete, light and temperature can increase to promote true leaf emergence and further plug growth.

It is best to group crops based on their temperature sensitivity to provide the best growing conditions and produce a higher-quality crop. Stage 3 of plug production requires a higher light intensity than the previous stages (Hartmann et al., 2011). However, making enough light available to the crop during Stage 3 and 4 is more of a challenge during the winter and early spring months in Northern latitudes as not enough light can result in poor shoot and root growth (Styer, 2011). Thus, it is recommended to use a source of high-intensity discharge (HID) lamps such as high-pressure sodium (HPS) or light-emitting diodes (LEDs) to increase the radiation intensity and even extend the day length. High humidity can also impede plug growth by inhibiting calcium uptake, leading to stretched and soft shoots and reduced root growth (Styer, 2011). By Stage 4, soil temperatures and moisture availability should be reduced to slow root and shoot growth to “tone” the plug and make it ready for shipment or transplant (Hartmann et al., 2011; Styer, 2011).

A finished plug (Stage 4) must be pullable with an intact root system and a compact shoot and should be transplanted as soon as possible to prevent root-binding (Styer, 2011). The transplant medium should be different from the initial plug medium and provide well drainage (Styer, 2011). It is best to avoid saturating the transplanted plugs for the first week as well as using moderate light levels to prevent stress. Medium temperatures should be maintained at 18 to 21 °C for the first few days after transplant to promote root growth and then for some crops, reduced for the remainder of the grow-out stage (Styer, 2011).

Light

Plants can be classified into photoperiodic response groups based on the duration of light, or darkness, within a 24-h period which influences flower induction. The common photoperiodic response categories include long-day (LDP), short-day (SDP), and day-neutral plants (DNP). LDPs flower when the photoperiod is longer than a critical day length whereas SDPs flower when the photoperiod is shorter than the critical day length during a 24-h period (Thomas and Vince-Prue, 1997). These response groups can be further classified as either facultative or obligate. A facultative LDP will flower under short days but flowering is hastened under LDs such as ageratum (*Ageratum houstoniamum*), dianthus (*Dianthus chinensis*), sage (*Salvia* spp.), and snapdragon (Erwin and Warner, 2002; Mattson and Erwin, 2005; Thomas and Vince-Prue, 1997). In contrast, obligate LDPs such as African daisies (*Gazania rigens*) and lobelia (*Lobelia erinus*) only flower under LDs (Erwin and Warner, 2002; Mattson and Erwin, 2005). Vice versa, facultative SDPs such as cosmos (*Cosmos bipinnatus*) and zinnia (*Zinnia elegans*) will flower under LDs but flower faster under SDs (Erwin and Warner, 2002; Mattson and Erwin, 2005). Whereas, obligate SDPs such as Spanish flag (*Ipomoea lobata*) only flower under SDs (Erwin and Warner, 2002; Mattson and Erwin, 2005). DNPs flower under any photoperiod and include amaranth (*Amaranthus hybridus*), dwarf morning glory (*Convolvulus tricolor*), poppy (*Papaver rhoeas*), and thunbergia (*Thunbergia alata*) (Erwin and Warner, 2002; Mattson and Erwin, 2005).

Plants accumulate biomass and undergo photosynthesis through the process of radiant energy, otherwise known as light (Heins et al., 2000). The radiation intensity or quantity delivered to a plant over time is directly correlated with the photosynthetic efficiency, in which the rate of photosynthesis will increase as radiation intensity increases until the plant becomes saturated (Faust, 2011). Radiation quality and quantity are two important factors that influence plant growth and development.

Radiation quality is the spectral distribution of light or relative number of photons from a light source. Plants can perceive photosynthetically active radiation (PAR), which is the spectral range of radiation from 400 to 700 nm comprised of blue (B, 400 to 500 nm), green (G, 500 to 600 nm), and red (R, 600 to 700 nm) radiation which plants use in the process of photosynthesis (Runkle, 2006). However, plants can perceive other wavelengths such as UV-B (280 to 315 nm), UV-A (315 to 400 nm), and far-red (FR, 700 to 800 nm) radiation. Furthermore, radiation can be measured as the quantity of light over time and space. PAR is measured as the photosynthetic photon flux (*PPF*) in $\mu mol \cdot s^{-1}$ or the *PPFD* in $\mu mol \cdot m^{-2} \cdot s^{-1}$ to determine the range of photons within PAR that are available to a plant within a given space (Runkle, 2015). To put these terms into perspective, the *PPFD* of sunlight is 2,000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ on a clear summer day and a maximum of 1,000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ on a winter day (Faust, 2011). In addition to the *PPF* and *PPFD*, the total photon flux density (*TPFD*) accounts for wavelengths from approximately 380 to 780 nm and is also measured as $\mu mol \cdot m^{-2} \cdot s^{-1}$ (E.S. Runkle, personal communication). The amount of radiation plants perceives influences root growth, shoot growth such as lateral branches, stem diameter, leaf size and shape, as well as number of flowers, flower size, and time to flower (Faust, 2011). To understand why radiation plays such a vital role in plant morphology, photoreceptors must be discussed.

The two most important photoreceptor families are phytochrome and cryptochrome. Phytochrome primarily absorbs R and FR radiation with some absorption of B radiation while cryptochrome primarily absorbs UV-A and B radiation. There are two forms of phytochrome, the R radiation absorbing form (P_r) and the FR radiation absorbing form (P_{fr}) (Thomas and Vince-Prue, 1997). The R to FR radiation ratio (R:FR) is what controls plant development such as seed germination, flowering, and stem elongation (Heins et al., 2000; Thomas and Vince-Prue, 1997). As plants perceive a low R:FR, P_r absorbs R radiation and is converted to P_{fr} which promotes flowering in LDPs as well as seed germination but inhibits flowering in SDPs (Thomas and Vince-Prue, 1997). However, if the R:FR is high, P_{fr} is converted back to P_r and can inhibit flowering of LDPs and even seed germination but promotes flowering in SDPs (Thomas and Vince-Prue, 1997). A low R:FR can also induce the shade avoidance response in which the stem elongates and is typically seen with tightly spaced plants (Heins et al., 2000; Thomas and Vince-Prue, 1997). However, cryptochrome can mediate stem elongation if B radiation is present. For example, hypocotyl elongation and petiole stretching were reduced when lettuce (*Lactuca sativa*) seedlings were germinated under 30 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of B radiation (Hoenecke et al., 1992). Similarly, leaf area and petiole length of *Arabidopsis thaliana* grown under 50 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of B radiation were reported to be much shorter than those grown without B radiation (Eskins, 1992).

Radiation intensity can further be measured as the total amount of PAR available over the course of a 24-h period as the DLI in $mol \cdot m^{-2} \cdot d^{-1}$ (Korczynski et al., 2002). Across the U.S., the DLI can reach up to 60 $mol \cdot m^{-2} \cdot d^{-1}$ outside on a cloudless summer day and can be as low as 5 $mol \cdot m^{-2} \cdot d^{-1}$ during an overcast winter day (Korczynski et al., 2002). However, in Northern latitudes the DLI inside a greenhouse can be as low as 3 $mol \cdot m^{-2} \cdot d^{-1}$ during a cloudy winter day to 30 $mol \cdot m^{-2} \cdot d^{-1}$ on a clear summer day due to greenhouse infrastructure and hanging baskets intercepting solar radiation (Faust, 2011). For most plant species as DLI increases, total dry mass (TDM), lateral branching, and number of flowers increase while time to flower decreases. For instance, TDM of ageratum ‘Hawaii White’, African marigold ‘American Antigua Orange’ (*Tagetes erecta*), petunia ‘Apple Blossom’, salvia ‘Lady in Red’ (*Salvia coccinea*), vinca ‘Pacific Lilac’ (*Catharanthus roseus*), and zinnia ‘Dreamland Rose’ increased as the DLI increased from 5 to 43 $mol \cdot m^{-2} \cdot d^{-1}$ while TDM for wax begonia ‘Vodka Cocktail’ (*Begonia ×semperflorens-cultorum*) and impatiens ‘Cajun Red’ (*Impatiens walleriana*) increased from 5 to 19 $mol \cdot m^{-2} \cdot d^{-1}$ (Faust et al., 2005). As DLI increased from 5 to 43 $mol \cdot m^{-2} \cdot d^{-1}$, lateral branching of ageratum and petunia increased and time to flower decreased for ageratum, petunia, salvia, and zinnia (Faust et al., 2005). The greatest number of flowers were recorded at 43 $mol \cdot m^{-2} \cdot d^{-1}$ for African marigold, petunia, vinca, and zinnia, but doubled for wax begonia and impatiens as DLI increased from 5 to 19 mol·m^{-2}·d^{-1} (Faust et al., 2005). Furthermore, a reduction in time to flower was reported as DLI increased to 5.8 mol·m^{-2}·d^{-1} for cyclamen ‘Metis Scarlet Red’ (*Cyclamen persicum*) (Oh et al., 2009) and 10.6 mol·m^{-2}·d^{-1} for pansy ‘Delta Yellow Blotch’ and ‘Delta Primrose Blotch’ (*Viola ×wittrockiana*) (Niu et al., 2000).

To produce at least an average quality crop, a DLI between 10 to 12 mol·m^{-2}·d^{-1} is recommended. However, shade tolerant crops can tolerate much lower DLIs (Runkle, 2006). For example, commercially acceptable wax begonia and impatiens were produced under 5 mol·m^{-2}·d^{-1}, while 12 mol·m^{-2}·d^{-1} was adequate for ageratum, vinca, petunia, salvia, and zinnia (Faust et al., 2005). However, plant quality was greatest when grown at slightly higher radiation intensities. Typically, plant quality declines under a DLI of 5 mol·m^{-2}·d^{-1} or less and can lead to plants with little lateral branching, larger leaves, delayed flowering, and a reduction in water uptake (Faust et al., 2005). For example, subsequent flowering of celosia ‘Gloria Mix’ (*Celosia argentea* var *plumosa*) and salvia ‘Vista Red’ were delayed by 10 and 11 d, respectively, when seedlings were grown under a DLI of 4.1 mol·m^{-2}·d^{-1} compared to 14.2 mol·m^{-2}·d^{-1} (Pramuk and Runkle, 2005).

In addition, there is evidence that increasing the DLI to genera-specific maximums can promote root growth of vegetative propagated plants. When producing young plants, a DLI between 10 and 12 mol·m^{-2}·d^{-1} is generally conducive to root growth over shoot growth, which can lead to a more marketable liner (Lopez and Runkle, 2008; Currey et al., 2012). For example, shoot-tip cuttings of angelonia ‘AngelMist White Cloud’ (*Angelonia angustifolia*), argyranthemum ‘Madeira Cherry Red’ (*Argyranthemum frutescens*), diascia ‘Wink Coral’ (*Diascia barberae*), lantana ‘Lucky Gold’ (*Lantana camara*), nemesia ‘Aromatica Royal’ (*Nemesia fruticans*), osteospermum ‘Voltage Yellow’ (*Osteospermum ecklonis*), scaevola ‘Blue

Print' (*Scaevola hybrid*), bacopa 'Abunda Giant White' (*Sutera cordata*), and verbena 'Aztec Violet' (*Verbena ×hybrida*) increased in TDM, shoot dry mass (SDM), and root-to-shoot dry mass ratio (R:S) by 64%–465%, 50%–384%, and 18%–419%, respectively, as DLI increased from 1.2 to 12.3 $mol \cdot m^{-2} \cdot d^{-1}$ (Currey et al., 2012). Additionally, stem length of diascia, lantana, and nemesia increased as DLI increased but argyranthemum, osteospermum, and scaevola were unaffected (Currey et al., 2012). Stem caliper also increased as DLI increased for angelonia, argyranthemum, diascia, nemesia, osteospermum, and verbena but did not affect lantana, scaevola, or bacopa (Currey et al., 2012). Similarly, vegetative cuttings of New Guinea impatiens 'Harmony White', 'Harmony Magenta', and 'Celebrette Red' (*Impatiens hawkeri*) had an increase in root dry mass (RDM) by 867%, 604%, and 580% as well as SDM by 53%, 32%, and 40%, respectively, as DLI increased from 1.3 to 6.1 $mol \cdot m^{-2} \cdot d^{-1}$ (Lopez and Runkle, 2008). However, Hutchinson et al. (2012) found SDM to decrease as DLI increased from 1.2 to 12.3 $mol \cdot m^{-2} \cdot d^{-1}$ for cuttings of angelonia 'AngelMist White Cloud', verbena 'Aztec Violet', osteospermum 'Voltage Yellow', and nemesia 'Aromatica Royal' during propagation.

Supplemental lighting

Greenhouse operations can use SL to increase the DLI when solar radiation conditions are unconducive to promote adequate plant growth during cloudy days and winter months. SL is primarily provided by HID lamps such as HPS or metal halide lamps to extend or supplement solar radiation (Faust, 2011). It is the only appreciable way of increasing the *PPFD* during the low light conditions found during young plant production. For example, petunia 'Red Flash' seedlings had 68%–88% greater fresh mass, were compact and had darker foliage under HPS lamps providing a *PPFD* of 167 $\mu mol \cdot m^{-2} \cdot s^{-1}$ compared to no supplemental lighting (Graper and Healy, 1991).

As of 2017, 98% of greenhouses in the U.S. that utilized supplemental lighting used HPS and metal halide lamps (Stober et al., 2017). HPS lamps primarily emit wavelengths between 565 to 700 nm which includes yellow (565 to 590 nm), orange (590 to 625 nm), and R (625 to 700 nm), with some FR (700 to 800 nm) radiation. Approximately, 30% of the energy utilized by HPS lamps is converted into PAR with the rest emitted as heat. Additionally, bulbs have a relatively short lifespan of 10,000 luminous hours (Spaargaren, 2001). Newer double-ended HPS lamps now have a higher efficacy than previous models and provide uniform lighting, but they still emit radiant heat that can scorch the plant canopy if the lamp is too close (Stober et al., 2017). Other lighting fixtures, such as LEDs, have become available with applications for use in horticulture.

LEDs are solid-state semiconductors that can emit radiation from the UV-C range (250 nm) to infrared (1000 nm) (Bourget, 2008). Fixtures containing LEDs have been growing in popularity due to their efficiency and lifetime when compared to incandescent, fluorescent, and HID lamps (Bourget, 2008; Stober et al., 2017). However, depending on the spectral output, LEDs can vary in efficacy. White LEDs are slightly less efficient than monochromatic B LEDs because their phosphor coating fluorescence the light during the conversion process (Bourget, 2008). LED fixtures also slowly dim over time due to individual LEDs going out, in which manufacturers recommend replacing them when they reach 70% of the original radiation intensity (Bourget, 2008). LED fixtures do emit heat, but not to the proportion as HPS lamps, which allows them to be placed closer to plants than what has typically been recommended for supplemental lighting (Bourget, 2008).

Due to growing interest in manipulating the light spectra to produce high-quality crops, LEDs have been utilized in numerous studies in recent years to determine how crops perform compared to those under HID lamps. When unrooted cuttings of New Guinea impatiens

‘Celebrette Frost’, geranium ‘Designer Bright Red’ (*Pelargonium ×hortorum*), and petunia ‘Suncatcher Midnight Blue’ were grown under HPS or LEDs providing blue:red (B:R radiation ratios) of B_0:R_{100}, B_{15}:R_{85}, and B_{30}:R_{70}, there were no commercially significant differences between treatments (Currey and Lopez, 2013). In contrast, snapdragon ‘Rocket Pink’, vinca ‘Titan Punch’, impatiens ‘Dazzler Pearl Blue’, geranium ‘Bullseye Scarlet’, petunia ‘Plush Blue’, and African marigold ‘Bonanza Flame’ seedlings grown under B_{15}:R_{85} or B_{30}:R_{70} LEDs were more compact and had a higher stem caliper and sturdiness quotient than seedlings under HPS lamps (Randall and Lopez, 2014). Similarly, the stem length of gerbera ‘Jaguar Deep Orange’, impatiens ‘Accent Premium Salmon’, and petunia ‘Ramblin Peach Glo’ seedlings were reduced by 28%, 34%, and 48%, respectively, when grown under LEDs providing 90 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of PAR compared to those under HPS lamps (Hurt et al., 2019). Although there is evidence that B:R LED fixtures are promising for the future of greenhouse production of floriculture crops, the absence of FR radiation during production may pose as a problem when producing LDPs.

Since flowering of LDPs is hastened under a low R:FR, growers are concerned that flowering of these crops could be delayed under LEDs only providing B and R radiation. However, this can be solved by adding FR LEDs. For example, coreopsis ‘Sunfire’ (*Coreopsis grandiflora*), pansy ‘Matrix Yellow’, and petunia ‘Purple Wave’ flowered 2, 7, and 2 d earlier, respectively, under sole-source LEDs providing a radiation ratio of B_9:R_{84}:FR_7 compared to those under B_{13}:R_{87} (Craver et al., 2018). However, the addition of FR radiation also increased leaf area and stem caliper for coreopsis, pansy, and petunia but also increased stem length which is typically not desired (Craver et al., 2018). Similar results have been reported for impatiens ‘Super Elfin XP Red’, geranium ‘Pinto Premium Orange Bicolor’, petunia ‘Wave Blue’, and snapdragon

‘Trailing Candy Showers Yellow’ seedlings, which had an increase in leaf area and stem length with the addition or substitution of 16 to 64 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of FR radiation to B and R LEDs providing *PPFD*s of 96 to 160 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Park and Runkle, 2017). However, snapdragon was shorter and flowered 10 to 12 d earlier with the inclusion of ≥16 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of FR radiation during LED treatments (Park and Runkle, 2017).

As LEDs advance and the horticulture industry gradually adopts growing with specific lighting spectra, it is becoming apparent that there are still aspects we do not know about growing plants under LEDs. Due to plants having different responses to different radiation qualities and quantities, it is becoming increasingly important to research the best uses for implementing LEDs in controlled environments. There are still many unknowns for how LEDs can influence plant quality and how specific lighting spectra at the young plant stage may affect growth and development as the plant matures. It is apparent that additional research needs to be conducted on a broad array of plants to determine SL quality recommendations for young plant production.

Temperature

In addition to radiation, temperature plays a large role in developmental processes such as seed germination, rooting, flowering, production time, plant architecture and quality (Blanchard and Runkle, 2011). Understanding how the greenhouse average daily temperature (ADT) and a crop’s base (T_b) and optimal temperatures (T_{opt}) interact can be used to maximize plant development. The ADT, during a 24-h period, influences plant developmental rates such as leaf unfolding and time to flower (Blanchard and Runkle, 2011; Heins et al., 2000). In general, as the ADT increases, plant development rate also increases to a point, which can be defined based on a crop's T_{opt} (Heins et al., 2000). The T_b is the minimum temperature that a plant will undergo cell division. Between the T_b and T_{opt}, the rate of development is usually linear as plant cells divide and mature rapidly (Heins et al., 2000). Development slows once the temperature falls below the T_b or above T_{opt}. At and above the maximum temperature (T_{max}), development generally ceases and plant stress ensues (Heins et al., 2000).

Plants can be categorized as either cold-tolerant, cold-intermediate, or cold-sensitive depending on their T_b (Blanchard and Runkle, 2011). Cold-tolerant crops, such as gerbera, French marigold, and snapdragon have a T_b <4 °C while cold-sensitive crops, such as angelonia and New Guinea impatiens, have a T_b >7 °C (Blanchard and Runkle, 2011). Cold-intermediate species, including chrysanthemum (*Chrysanthemum ×grandiflorum*) and geranium, have a T_b between 4 and 7 °C (Blanchard and Runkle, 2011). Most crops are typically grown 11 to 17 °C above the T_b as the ADT needs to increase for plant development to increase (Blanchard and Runkle, 2011). However, plant development can quickly decline if plants are grown above the T_{opt} mainly due to heat stress, so most crops should be grown between the T_b and T_{opt} (Blanchard and Runkle, 2011).

The T_{opt} varies amongst species and in general a T_{opt} of 21 °C is typical for cool-season crops while a T_{opt} of 32 °C is representative of warm-season crops (Blanchard and Runkle, 2011). At low temperatures, plant development becomes slow and the transport of nutrients becomes minimal, which can lead to nutrient deficiencies in some plants that are cold-intermediate and cold-sensitive (Blanchard and Runkle, 2011). In addition, implementing low growing temperatures can use more energy than necessary because plant development slows, taking longer for a crop to develop and flower compared to a crop grown warm and finishing faster (Blanchard and Runkle, 2011). Such is the case with petunia 'Dreams Neon Rose' and French marigold ‘Janie Flame’, where time to flower decreased from 36 to 17 d and 33 to 17 d, respectively, as the ADT increased from 14 to 26 °C, respectively, under a DLI of 12 $mol \cdot m^{-2} \cdot d^{-1}$. Growers that lower the greenhouse ADT to save on energy cost, can spend 3% to 5% more on energy when the mean temperature is 14 °C compared to 23 °C (Blanchard et al., 2009). Similarly, Vaid and Runkle (2014) reported that petunia ‘Wave Purple Classic’, ‘Easy Wave Neon Rose’, and ‘Wave Purple Improved’ flowered 59, 31, and 49 d earlier, respectively, when grown at an ADT of 21 °C compared to 16 °C.

Root-zone heating

Media temperature influences seed germination and rooting of vegetative cuttings with recommended temperatures ranging from 22 to 25 °C but vary with species and even the growing stage (Blanchard and Runkle, 2011). Root-zone heating (RZH) has been widely studied over the past half century as greenhouse growers look for solutions to regulate media temperature while avoiding increasing energy costs. Today, RZH is commonly implemented by either a bench or floor system in which recirculating hot water travels through inlaid pipes to heat the substrate (Hartmann et al., 2011).

Using RZH has proven to reduce energy consumption by up to 50% when the air temperature is lowered without sacrificing plant quality (Sachs et al., 1992). When RZH is higher than the air temperature, the leaf temperature of a plant will generally be closer to the RZH set point than the air temperature and thus create a microclimate for the plant (Vogelezang and van Weel, 1989). This microclimate can hasten developmental rates because the plant temperature is higher than its surrounding environment. For example, Olberg and Lopez (2017) reported that leaf temperature of petunia cultivars increased on average of 1.7 °C with RZH compared to plants with no RZH. Additionally time to flower of petunia ‘Sun Spun Lavender Star’, ‘Sun Spun

Burgundy', 'Supertunia Red', 'Supertunia Bordeaux', and 'Sanguna Patio Red' grown at an air temperature of 15 °C and a RZH set point of 27 °C was reduced by 9, 7, 13, 11, and 8 d, respectively, compared to an air temperature of 15 °C with no RZH (Olberg and Lopez, 2017). A similar response occurred for African violet 'Rhapsody 19' and 'Rhapsody 49' (*Saintpaulia ionantha*) when grown at an RZH set point of 25 °C and an air temperature of ≈20 °C, where flowering was reduced by 7 to 14 d compared to no RZH with an air temperature of ≈19 °C (Vogelezang, 1988). In addition to influencing time to flower, RZH can affect SDM and RDM depending upon species.

When cuttings of chrysanthemum 'May Shoesmith' were rooted with RZH set points of 23 and 29 °C, they were compact and yielded a 33% to 27% reduction in SDM than the unheated control of 17 °C or RZH of 26 °C, respectively (McAvoy and Janes, 1983). Furthermore, under an ADT of 12 °C and RZH set point of 16 °C, chrysanthemum SDM was reduced by 13%–21% and 10%–18% compared to an ADT of 12 °C and RZH set points of 18 and 20 °C, respectively (McAvoy and Janes, 1983). Although the general increase in SDM with increasing RZH was reported for chrysanthemum, other researchers have shown a decrease in SDM with increasing RZH for finished plants of petunia (Olberg and Lopez, 2017), African violet (Vogelezang, 1988), and New Guinea impatiens (Meyer et al., 1993).

Production time can also be influenced by RZH. Rooting time of dwarf umbrella tree 'Compacta' (*Schefflera arboricola*) and weeping fig (*Ficus benjamina*) cuttings were reduced by up to 2.5 weeks when they were grown at an air temperature of 20 to 23 °C with RZH set points of 20, 25, and 30 °C compared to the unheated control with an air and RZH set point of 19 °C (Vogelezang, 1991). The different temperature treatments did not have a large visual impact on the quality of the crops and researchers found that air temperature was more important for growth than root-zone temperature (Vogelezang, 1991).

From previous research, it is recommended to use RZH of 23 to 25 °C with an air temperature of 21 to 23 °C during root initiation as these conditions promote rapid root growth and less stem growth (Blanchard et al., 2006). Once roots are initiated, both RZH and air temperature should decrease to 19 to 21 °C and 18 to 21 °C, respectively (Blanchard et al., 2006). However, these requirements may not be the same across species as Loach (1988) determined that RZH should be 18 to 25 °C for cool-season species and 25 to 32 °C for warm-season species. In addition, Hartmann et al. (2011) noted that some temperate plant species are propagated in environments with air day and night temperatures of 21 to 27 °C and 15 °C, respectively. Although there are discrepancies in the literature regarding the ideal RZH temperature set point, most outcomes from using RZH have shown a promotion in root growth, leading to higher root dry mass and uniformity (Carpenter et al., 1973; Owen and Lopez, 2018).

One of the most studied plants during propagation is poinsettia (*Euphorbia pulcherrima*). Carpenter et al. (1973) exposed callused terminal stem cuttings of poinsettia 'Eckespoint D-3' to RZH ranging from 5 to 35 °C and day/night air temperature of 24/18 °C for 1, 3, or 5 d after initially propagating in a common environment for 14, 16, or 18 d. RZH of 25 to 30 °C for 3 to 5 d yielded the highest number of roots per cutting but RZH of 30 °C negatively impacted root growth 5 d after the treatment (Carpenter et al., 1973). It was determined that RZH of ≤15 °C and 35 °C have inhibitory effects on root growth and development for poinsettia (Carpenter et al., 1973). Similarly, Gislerød (1983) found that root number and length were maximized at RZH of 24 and 28 °C with an air temperature of 21 °C after 17 d of propagation for poinsettia 'Lady' cuttings. However, a more recent study discovered that a RZH set point of 26 to 28 °C with an air temperature of 24 °C resulted in 100% rooting and yielded the most roots per cutting for poinsettia ‘Freedom Dark Red’ 19 d after cuttings were placed in the propagation environment (Wilkerson et al., 2005). Although RZH set points of 25 to 30 °C produce well-rooted poinsettia liners, it is apparent from these studies that RZH may be cultivar dependent, which has been a known underlying factor for quite some time (Cooper, 1973).

Root-zone heating has also been reported to increase rooting percentage in softwood terminal cuttings of candytuft (*Iberis semperflorens*) in which 90% of cuttings rooted with RZH of 22 °C and a day/night air temperature of 14 to 16 °C and 10 to 12 °C, respectively, compared to no rooting when RZH was not utilized (Iapichino and Bertolino, 2007). Similarly, Owen and Lopez (2018) reported that rooting success of purple fountain grass (*Pennisetum ×advena*) culm cuttings was 85%, 90%, 100%, and 100% with a RZH set point of 21, 23, 25, and 27 °C, respectively, and air temperature of 23 °C with a DLI of 10 $mol \cdot m^{-2} \cdot d^{-1}$. RDM of purple fountain grass also increased as DLI increased from 4 to 10 $mol \cdot m^{-2} \cdot d^{-1}$ and RZH increased from 21 to 27 °C (Owen and Lopez, 2018). Other studies have propagated cuttings successfully with RZH. However, there is a gap in the literature for the effects of RZH on other economically important ornamental crops. Thus, it is difficult to determine what environmental conditions are adequate for optimal liner production of herbaceous ornamentals with different T_b.

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SECTION II

PROPAGATION OF HERBACEOUS UNROOTED CUTTINGS OF COLD-TOLERANT SPECIES UNDER REDUCED AIR TEMPERATURE AND ROOT-ZONE HEATING

Propagation of herbaceous unrooted cuttings of cold-tolerant species under reduced air temperature and root-zone heating

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Abstract

The majority of vegetative propagation of herbaceous cuttings occurs in greenhouses during late winter and early spring when radiation quantity and average daily temperature (ADT) outdoors are seasonally low. To promote rapid callus induction and rooting, supplemental lighting and air and root-zone heating (RZH) can be utilized. Given that cold-tolerant crops have base temperatures <4 °C, reducing the air temperature is a potential energy saving strategy. Therefore, the objective of this study was to quantify how reduced air ADT and increased RZH temperatures influence root initiation and development of cold-tolerant herbaceous annual and perennial crops propagated by cuttings. Shoot-tip cuttings of calibrachoa 'Callie Coral' (*Calibrachoa* ×*hybrida*), campanula 'Birch Hybrid' (*Campanula portenschlagiana*), nemesia 'Aromatica Royal Blue' (*Nemesia fruticans*), nepeta 'Junior Walker' (*Nepeta* ×*faassenii*), osteospermum 'Voltage Yellow' (*Osteospermum ecklonis*), petunia 'Sanguna Patio Blue' (*Petunia* ×*hybrida*), phlox 'Glamour Girl' (*Phlox paniculata*), and rosemary 'Arp' (*Rosmarinus officinalis*) were inserted into a soilless medium and grown in a greenhouse with an air ADT and RZH temperature of 21 and 24 °C, respectively, for callusing. After 6 d, trays of cuttings were placed in two greenhouse compartments with air ADTs of 16 or 21 °C. Three benches within each compartment had RZH set points of 21, 24, or 27 °C. After 14 d, the interaction of air and RZH temperatures influenced stem length of nepeta, petunia, phlox, and rosemary. For example, increasing the air ADT from 16 to 21 °C and RZH set points from 21 to 27 °C increased stem length of nepeta by 2.5 to 3.7 cm. As air ADT increased from 16 to 21 °C at an RZH set point of 27 °C, shoot dry mass increased by 32% and 24% for calibrachoa and phlox, respectively. Root dry mass and liner pullability for osteospermum increased as air ADT increased from 16 to 21 °C at an RZH set point of 21 °C by 14 mg and 70%, respectively. Overall, the results from this

study identify cold-tolerant crops that can be propagated with genera-specific RZH set points under reduced air ADT without sacrificing liner quality or propagation time and highlights the importance of RZH for growers.

Keywords: annual bedding plants, average daily temperature, perennials, propagation, vegetative cuttings

Abbreviations: ADT, average daily temperature; DLI, daily light integral; *PPFD*, photosynthetic photon flux density; QI, quality index; R:S, root-to-shoot ratio; RDM, root dry mass; RZH, root-zone heat; SDM, shoot dry mass; T_b, base temperature; T_{max}, maximum temperature; T_{opt}, optimal temperature; VPD, vapor-pressure deficit

Introduction

Ornamental herbaceous annual and perennial plants can be propagated by either seed, tissue culture, or vegetative shoot-tip cuttings. Advantages of vegetative cutting propagation include shorter production time, the ability to produce sterile or seedless cultivars, and increased genetic uniformity and true-to-type plants (Erwin, 1995). In 2018, the wholesale value for propagative annual bedding plant and herbaceous perennial material in the United States (U.S.) was U.S. $197 million and $116 million, respectively (USDA, 2019). Generally, annual bedding/garden plant propagation takes place during late winter and early spring to meet spring and summer sales. However, due to low ambient irradiance levels and temperatures in Northern latitudes, growers in these regions use supplemental lighting, heating, or a combination of the two to provide adequate environmental growing conditions.

Light and temperature are the utmost important environmental parameters for plant growth and development, respectively. Light is the primary driver of biomass accumulation and growth, while temperature regulates the rate of plant development and crop timing (Heins et al., 2000). The interaction of these two environmental parameters is what determines overall plant quality (Heins et al., 2000). Photosynthetic daily light integral (DLI) directly influences herbaceous plant biomass accumulation (Blanchard et al., 2006). For example, increased DLIs increased root dry mass (RDM) and shoot dry mass (SDM) of petunia (*Petunia* ×*hybrida*), New Guinea impatiens (*Impatiens hawkeri*) (Lopez and Runkle, 2008), angelonia (*Angelonia angustifolia*), argyranthemum (*Argyranthemum frutescens*), diascia (*Diascia barberae*), lantana (*Lantana camara*), nemesia (*Nemesia fruticans*), osteospermum (*Osteospermum ecklonis*), scaevola (*Scaevola hybrid*), bacopa (*Sutera cordata*), and verbena (*Verbena* ×*hybrida*) cuttings (Currey et al., 2012).

Temperature influences many developmental (root and shoot development), physiological (photosynthesis, respiration, and transpiration), and morphological (stem elongation) processes during cutting propagation (Blanchard et al., 2006; Moe and Heins, 1990). As temperature increases above the species-specific base temperature (T_b), developmental rates increase because cell division and expansion increase until an optimum temperature is reached (T_{opt}), above which developmental rate declines until a maximum temperature (T_{max}) is reached and development ceases (Heins et al., 2000; Kester, 1970). A general recommendation is that the air temperature during cutting propagation should be 24 to 27 °C during the day and 21 to 23 °C at night (Blanchard et al., 2006). The energy used to heat greenhouses to provide proper environmental conditions is the second largest production cost, and seasonally can account for up to 30% of total operating expenses (Lopez and Runkle, 2014). Growers have been mitigating energy costs by reducing the air temperature, installing energy curtains, using root-zone heating (RZH), or even closing down for parts of the year (Brumfield et al., 2009).

Some commercial greenhouses are equipped with either bench-top or bottom-floor RZH systems. However, RZH set points are sometimes the same temperature as the air average daily temperature (ADT) (Vogelezang and van Weel, 1989) even though previous studies have reported that energy costs can be reduced when plants are grown with higher root-zone and lower air ADTs. For instance, Sachs et al. (1992) reported a 50% reduction in energy costs when seedlings and rooted cuttings were grown on bench-tops with an RZH temperature of 25 °C and a reduced air temperature of 23/18 °C (day/night) compared to no RZH. Although energy costs were reduced, there were no differences in RDM, SDM, root-to-shoot ratio (R:S), time to flower or number of flowers when tomato ‘Ace 55 VF’ and ‘Boy hybrid’ (*Lycopersicon esculentum*) and chrysanthemum ‘Bright Golden Anne’ and ‘Circus’ (*Chrysanthemum morifolium*) were grown with or without RZH and a reduced air ADT (Sachs et al., 1992). Additionally, Vogelezang and van Weel (1989) determined that bench-top RZH increased the leaf temperature and created a microclimate around begonia (*Begonia ×hiemalis*), kalanchoe (*Kalanchoe* spp.), and African violet (*Saintpaulia ionantha*). Similarly, Olberg and Lopez (2017) found that increasing the RZH temperature to 27 °C and reducing the air ADT to 15 °C increased leaf temperature by an average of 1.7 °C compared to an air ADT of 20 °C with no RZH (control) during the production of numerous petunia cultivars. By using RZH, the plant temperature increased, and the rate of developmental increased. For instance, time to flower of petunia ‘Supertunia Red’ decreased by 13 d when plants were grown at an air ADT of 15 °C and RZH set point of 27 °C compared to an air ADT of 20 °C with no RZH (Olberg and Lopez, 2017).

However, the results of utilizing RZH can be variable depending on the cold-tolerance of the crop (Gerovac, 2014).

Cold-tolerant crops are those with an estimated T_b <4 °C (Blanchard and Runkle, 2011a). Typically, cold-tolerant species can be grown at lower ADTs compared to cold-sensitive crops, whose T_b is >7 °C (Blanchard and Runkle, 2011a). This can be advantageous for cold-tolerant crops as heating may be unnecessary and possibly reduce plant quality. For example, Wai and Newman (1992) grew cold-tolerant ‘Rainier White’ and cold-sensitive ‘Tampico’ cut-flower snapdragon (*Antirrhinum majus*) in a greenhouse with a day temperature of 26 °C, night temperature of 13 or 20 °C, and RZH set points of 10 or 26 °C. ‘Rainier White’ had longer stems when grown at a night air and RZH temperature of 20 and 10 °C, respectively, while ‘Tampico’ had longer stems at a night air and RZH temperature of 20 and 26 °C, respectively (Wai and Newman, 1992). From this case, it is apparent that the cold-tolerant snapdragon grew best in low RZH conditions as longer stem lengths are desirable for cut-flower production. However, stem length is not always desirable for plant propagation.

Furthermore, Gerovac (2014) forced several bedding plant species at an air ADT of 16 °C and RZH temperatures of 18, 21, 24, and 27 °C and compared them to plants grown at an air temperature of 20/18 °C (day/night) without RZH. Stem elongation as well as RDM and SDM for the cold-tolerant French marigold ‘Durango Bee’ (*Tagetes patula*) were similar when grown at an air ADT of 16 °C and either no RZH or RZH set points of 18, 21, 24, and 27 °C as those grown at an air temperature of 20/18 °C (day/night) and no RZH. In contrast, development of a cold-sensitive crop such as New Guinea impatiens ‘Celebration Red’ was significantly delayed when grown at an ADT of 16 °C with or without RZH (Gerovac, 2014). It is apparent that cold-tolerant crops can be grown at low air temperatures with or without RZH and not cause a reduction in plant quality such as stem length, RDM, and SDM. This finding suggest that cold-tolerant crops could be propagated at lower air and RZH temperatures than current recommendations suggest.

In general, it appears that the RZH T_{opt} during propagation is between 20 to 28 °C but differs for cool-season and warm-season crops and should typically be higher for callusing and lowered for root growth (Dykeman, 1976; Hartmann et al., 2011; Loach, 1988). For example, the RZH T_{opt} for unrooted cuttings of poinsettia 'Lady' (*Euphorbia pulcherrima*) was between 24 and 28 °C depending on media type and at an air ADT of 21 °C (Gislerød, 1983). Additionally, unrooted cuttings of chrysanthemum 'Bright Golden Anne' and forsythia 'Lynwood' (*Forsythia ×intermedia*) developed more roots and had higher RDM when exposed to RZH temperatures of 30 °C for root initiation and then 25 °C for root growth (Dykeman, 1976). Outside of these general guidelines, no research to our knowledge has identified RZH temperature guidelines for rooting cuttings of cold-tolerant herbaceous annual bedding and perennial plants with the exception of blanket flower 'Gallo Red' (*Gaillardia aristata*), coral bells 'Black Beauty' (*Heuchera hybrida*), and wand flower 'Siskiyou Pink' (*Gaura lindheimeri*) (Owen, 2017).

Therefore, the objectives of this study were to quantify the interaction between air and bench-top RZH temperature during propagation of cold-tolerant herbaceous annual and perennial shoot-tip cuttings on root initiation and development in order to produce high-quality, compact, and uniform liners. From these findings, we hope to establish new guidelines for propagating cold-tolerant annuals and perennials with RZH and reduced air temperatures to reduce greenhouse heating costs while maintaining plant quality.

Materials and methods

Plant materials

Unrooted 2 to 4.5 cm herbaceous stem-tip cuttings of campanula ‘Birch Hybrid’ (*Campanula portenschlagiana*), nemesia ‘Aromatica Royal Blue’ (*Nemesia fruticans*), nepeta ‘Junior Walker’ (*Nepeta ×faassenii*), and phlox ‘Glamour Girl’ (*Phlox paniculata*) (Ball Horticultural Co., West Chicago, IL) were received on 23 Oct., 20 Nov. 2017, and 08 Jan. 2018. Osteospermum ‘Voltage Yellow’ (*Osteospermum ecklonis*) (Ball Horticultural Co., West Chicago, IL) was received on 27 Nov. 2018; calibrachoa ‘Callie Coral’ (*Calibrachoa ×hybrida*), petunia ‘Sanguna Patio Blue’ (*Petunia ×hybrida*) (2 to 3 cm in length; Syngenta Flowers, LLC, Gilroy, CA) and rosemary ‘Arp’ (2 cm in length; *Rosmarinus officinalis*) (Dümmen Orange NA, Inc., Columbus, OH) were received on 08 Jan. and 05 Feb. 2019.

Cuttings of campanula, nemesia, nepeta, and phlox were placed in 72-cell trays (44-mL individual cell volume; T.O. Plastics, Inc., Clearwater, MN) and cuttings of calibrachoa, osteospermum, petunia, and rosemary were placed in 72-cell trays (28-mL individual cell volume; Landmark Plastics, Akron, OH) filled with a 50:50 (v/v) commercial soilless substrate composed of 70% peat moss, 21% perlite, and 9% vermiculite (Suremix; Michigan Grower Products Inc., Galesburg, MI) and 50% coarse perlite. Trays of calibrachoa, osteospermum, petunia, and rosemary were divided into 36-cell trays to represent two blocks for each genera per treatment.

Callus greenhouse environmental conditions

The trays were then placed in a glass-glazed greenhouse with an air ADT set point of 21 °C and a vapor-pressure deficit (VPD) of 0.3 kPa in the Plant Science Research Greenhouse ranges at Michigan State University [(MSU), East Lansing, MI (lat. 43° N)] and on propagation benches with an RZH set point of 24 °C for 6 d to callus. To achieve an average daily light integral (DLI) of ≈5 $mol \cdot m^{-2} \cdot d^{-1}$, each bench was covered with shade cloth providing ≈52% shade (Solaro 5220 D O; Ludvig Svensson US, Inc., Charlotte, NC) under ambient daylight supplemented with a photosynthetic photon flux density (*PPFD*) of 62 ± 6 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at cutting height [as measured with a quantum sensor (LI-250A light meter; LI-COR Biosciences, Lincoln, NE)] delivered from high-pressure sodium [(HPS) LR48877; P.L. Light Systems; Beamsville, ON, Canada] lamps from 0600 to 2200 HR and when the outdoor light intensity was below ≈440 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Averages of air, plant, and RZH temperatures, DLI and VPD (as described above) during callusing are reported in Table 1.

Post-callus greenhouse environment

After 6 d of callusing, trays were randomly placed on propagation benches in one of two glass-glazed greenhouse compartments with an air ADT of 16 or 21 °C and a VPD of 0.3 kPa. Three benches in each greenhouse compartment were heated using a closed-loop bench-top RZH system with micro-tubing to circulate hot water (55 °C) across each bench to achieve RZH temperature set points of 21, 24, and 27 °C (Biotherm® Benchwarmer Kit; TrueLeaf Technologies, Petaluma, CA). To distribute bench heat evenly, cellofoam-expanded polystyrene boards provided insulation while the micro-tubing was covered with 2-mm thick galvanized sheet metal as well as high-temperature aluminum tape to affix the sheet metal to the benches. Benches were then covered with a 4-mil black construction film.

The photoperiod was 16 h (0600 to 2200 HR) consisting of natural day lengths with supplemental lighting from HPS lamps that delivered a *PPFD* of 114 ± 29 $\mu mol \cdot m^{-2} \cdot s^{-1}$ [as measured with a quantum sensor (LI-250A light meter; LI-COR Biosciences)] at plant height when outdoor light intensity was below ≈440 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

Overhead mist containing reverse-osmosis water supplemented with water-soluble fertilizer (MSU Plug Special 13N–2.2P–10.8K; Greencare Fertilizers, Inc., Kankakee, IL) and a micronutrient supplement (M.O.S.T.; JR Peters, Inc., Allentown, PA) was provided as necessary and delivered the following ($mg \cdot L^{-1}$): 60 N, 10 P, 50 K, 28 Ca, 5 Mg, 27 S, 16 Fe, 10 Zn, 17 Mn, 5 Cu, 3 B, and 0.2 Mo. The mist was regulated by an environmental computer that was a function of time and accumulated *PPFD*. A line quantum sensor (Apogee Instruments, Inc.; Logan, UT) positioned in the center of the propagation house recorded light intensity every 10 s. When the integrated light intensity reached 0.20 $mol \cdot m^{-2}$ or after 60 min., whichever first occurred, the overhead mist (operated from 0500 to 2400 HR) would turn on for 5 s. A VPD of 0.3 kPa was maintained by the injection of steam.

Light intensity for each bench was recorded every 10 s with a quantum sensor (LI-190R; LI-COR Biosciences) positioned in the middle of the bench. Infrared sensors were positioned 2.0 cm above leaves on all benches to record representative plant temperatures across treatments. A 72-cell tray filled with soilless substrate was placed in the middle of each bench. Three holes were made in three cells along the long edge of the tray where two thermocouples and a thermistor were inserted 2.6 cm below the substrate to record RZH. Each greenhouse compartment had a shielded and aspirated Priva Environmental Monitoring Box (Integro 725-3030; Priva North America, Vineland Station, ON, Canada) to measure the air ADT and control the VPD using thermocouples and a wick sitting in a small container of water inside the box. Averages of air, plant, and RZH temperature, DLI, and VPD are reported in Table 2.

Data collection

Data were collected 14 d after cuttings were placed on the RZH treatments. Eight or 10 cuttings of each genera per treatment were removed from propagation trays and the propagation substrate was gently rinsed from the roots. Cuttings of calibrachoa, osteospermum, petunia, and rosemary were assessed for pullability (i.e. plant is pulled from tray with all substrate intact) with anything less than 95% of all substrate was not considered pullable. Stem length, stem caliper, and reproductive status were assessed. Stem length was measured with a ruler from the base of the cutting to the apical meristem while stem caliper was measured below the lowest leaf with a digital caliper (41101 DigiMax; Wiha Switzerland, Monticello, MN). Reproductive status of the cutting was determined by macroscopic visible flower bud or flower for cuttings of calibrachoa, osteospermum, petunia, and rosemary only. After measurements, roots, stems, and leaves were excised and dried separately at 70 °C for 3 d before recording the root, stem, and leaf dry weights. Data calculated for each cutting included total dry mass (TDM), root-to-shoot ratio (R:S), sturdiness quotient (SQ), and quality index (QI). The SQ was calculated as shoot length divided by stem caliper. The QI, an objective, integrated, and quantitative measurement of floriculture plug quality, was calculated as [TDM × (R:S + SQ)] (Currey et al., 2013).

Experimental design and statistical analyses

The experiments used a randomized complete block design in a factorial arrangement and the experiments were replicated two or three times over time. The experimental factors were air ADT (2 levels) and RZH temperature (3 levels). Cuttings were randomly assigned to each air ADT and RZH temperature treatment which were randomized across benches within the greenhouse. Each experiment was replicated twice across propagation benches with 8 or 10 samples (individual cuttings) per block per ADT × RZH. Data were analyzed using SAS (version 9.2; SAS Institute, Cary, NC) mixed model procedure (PROC MIXED) for analysis of variance (ANOVA), and means were separated by Tukey’s honest significant difference (HSD) test at $P \leq 0.05$.

Results

Increasing the air ADT or RZH increased stem length of calibrachoa, nemesia, nepeta, and rosemary while it had variable effects on petunia and phlox and had no effect on campanula or osteospermum (Tables 3 and 4). For example, increasing RZH set points from 21 to 27 °C when the air ADT was 21 °C increased stem length by 16%, 14%, and 13% in calibrachoa, rosemary, and nemesia, respectively. As air temperature increased from 16 to 21 °C, stem length of nemesia increased from 54 to 58% at an RZH set point on 24 and 27 °C, respectively. Furthermore, the interaction of air ADT and RZH influenced stem length of nepeta, petunia, phlox, and rosemary. For instance, as air ADT increased from 16 to 21 °C, stem length of nepeta increased by 37% and 49% at RZH set points of 21 and 27 °C, respectively.

Neither air ADT nor RZH temperature influenced stem caliper of any genera studied except petunia (Table 3). At an air ADT of 16 °C, stem caliper of petunia was greater at an RZH set point of 24 °C compared to an RZH set point of 27 °C, and the smallest stem caliper was observed at an air ADT of 21 °C and RZH set point of 27 °C (data not presented).

Air ADT and RZH temperature interacted to influence the QI of nepeta and phlox (Tables 3 and 4). For nepeta, as air ADT increased from 16 to 21 °C, the QI increased by 38% to 83% as the RZH set points increased from 21 to 27 °C. Additionally, the highest QI was recorded at an air ADT of 21 °C and RZH temperature of 27 °C for nepeta. Increasing air ADT increased the QI of calibrachoa, nemesia, and nepeta but varied for phlox while RZH increased the QI of petunia and was variable for nemesia and nepeta. For example, the QI of calibrachoa increased by 42% as the air ADT increased from 16 to 21 °C at an RZH set point of 27 °C. In contrast, the QI of phlox decreased as the air ADT increased from 16 to 21 °C at an RZH set point of 21 °C and further decreased under an air ADT of 16 °C while RZH increased from 21 to 27 °C. The individual effects of air ADT or RZH temperature did not influence the QI of campanula, osteospermum, or rosemary.

The RDM of calibrachoa, nemesia, and rosemary were influenced by RZH temperature while air ADT influenced the RDM of campanula, nepeta, and rosemary (Tables 3 and 5). Regardless of air ADT, the greatest calibrachoa RDM was observed at an RZH set point of 21 °C while nemesia and rosemary produced the highest RDM at an RZH set point of 24 °C (Tables 3 and 5). Additionally, at an RZH set point of 24 °C, the RDM of rosemary was 26% greater at an air ADT of 16 °C compared to 21 °C. As the RZH set point increased from 21 to 27 °C at an air ADT of 21 °C, RDM of petunia decreased by 27%, and as the air ADT increased from 16 to 21 °C at an RZH set point of 27 °C, the RDM decreased by 24%. As air ADT increased from 16 to 21 °C, the RDM of osteospermum propagated at an RZH set point of 21 °C increased by 74%. The RDM of phlox was not influenced by air ADT, RZH, or their interaction.

Increasing the air ADT increased the SDM of calibrachoa, nemesia, and nepeta while RZH increased SDM of nepeta and variably influenced nemesia, petunia, and rosemary (Tables 3 and 5). As air ADT increased from 16 to 21 °C, SDM of nemesia and nepeta increased regardless of the RZH set point. As RZH set points increased from 21 to 27 °C, the SDM of nepeta increased by 23% and 28% at an air ADT of 16 and 21 °C, respectively. Furthermore, the SDM of nepeta and nemesia was lower at an air ADT of 16 °C compared to 21 °C for all RZH set points. The air ADT and RZH temperature interacted to influence SDM of calibrachoa, petunia, and phlox. For instance, the highest SDM of phlox was measured at an air ADT of 16 °C and RZH set point of 21 °C but was not significantly different from an air ADT of 21 °C and RZH set point of 27 °C. As RZH set points increased from 24 to 27 °C at an air ADT of 16 °C, SDM of calibrachoa and petunia cuttings decreased. However, the SDM of calibrachoa increased by 32% as the air ADT increased from 16 to 21 °C at an RZH set point of 27 °C. Neither air ADT nor RZH temperature had an effect on the SDM of campanula or osteospermum.

As air ADT increased, the R:S of osteospermum increased, calibrachoa, nemesia and nepeta decreased, and rosemary was variable (Tables 3 and 5). For example, the R:S of calibrachoa decreased by 19% when propagated at an air ADT of 21 °C and RZH set point of 27 °C compared to an air ADT of 16 °C. At an air ADT of 16 °C and RZH set points of 21 and 27 °C, the R:S was 11% and 32% greater for nemesia and 30% and 14% greater for nepeta, respectively, compared to an air ADT of 21 °C. The interaction of air ADT and RZH temperature influenced the R:S of osteospermum. At an air ADT of 16 °C and RZH set point of 21 °C, the R:S of osteospermum decreased by 39% and 36% compared to RZH set points of 24 and 27 °C, respectively. At an RZH set point of 21 °C, as the air ADT increased from 16 to 21 °C, the R:S of osteospermum increased by 57%. Neither the air ADT nor RZH set point influenced the R:S of campanula and phlox.

The highest percentage of pullable osteospermum liners was recorded at an RZH set point of 24 °C, regardless of air ADT (Table 3 and 6). Neither air nor RZH temperature had an effect on the liner pullability of calibrachoa, petunia, or rosemary. Air ADT influenced the percentage of calibrachoa rooted cuttings with visible flower buds and flowers (Table 3 and 6). At an RZH set point of 21 °C, the percentage of calibrachoa with visible buds was lower at an air ADT of 16 °C compared to 21 °C. Neither air ADT nor RZH temperature had an impact on the percentage of osteospermum, petunia, or rosemary rooted cuttings with visible buds or flowers. Under all treatments, nearly all petunia rooted cuttings had visible flower buds while osteospermum and rosemary had few to no visible flower buds or flowers.

Discussion

High-quality young plants and liners are compact, have thick stems, small leaves, and adequate root and shoot mass for successful shipping and transplanting (Currey et al., 2013; Klopmeyer et al., 2011; Lopez and Runkle, 2008). Although not limited to temperature, responses such as SDM, RDM, R:S, and plant height generally increase as RZH temperature increases (Cooper, 1973). Similarly, in the current study, increasing either the air ADT or RZH temperature usually increased stem length of calibrachoa, nemesia, nepeta, petunia, and rosemary. For example, at an air ADT and RZH set point of 16 and 21 °C, respectively, stem length of nepeta nearly doubled as it increased from 6.7 to 11.2 cm as air ADT and RZH set points increased to 21 and 27 °C, respectively (Table 4). However, taller rooted cuttings of ornamentals are usually not desirable for a variety of reasons. In contrast, previous studies have reported that stem length generally decreased as RZH temperature increased. Owen (2017) reported that stem length of blanket flower 'Gallo Red' at an air ADT of 21 °C decreased by 0.9 cm as RZH temperature increased from 20 to 28 °C. Additionally, stem length of petunia 'Supertunia Red', 'Supertunia Bordeaux', and recombinant inbred line IA160 at first open flower decreased by 24%, 21%, and 19%, respectively, when grown at an air ADT of 15 °C and RZH temperature of 27 °C compared to an air temperature of 15 °C without RZH (Olberg and Lopez, 2017). The relationship of stem length and air and RZH temperature during rooting can possibly be genera-, air temperature- or light-dependent, the latter of which was reported for coral bells 'Black Beauty' and wandflower 'Siskiyou Pink' (Owen, 2017). Whereas, Blanchard et al. (2011) reported stem length of petunia 'Easy Wave Coral Reef' and 'Wave Purple' increased by roughly 67% and 80%, respectively, as air ADT increased from 14 to ≥22 °C. The majority of crops in this study however, had shorter or equal stem lengths at an air ADT of 16 °C compared to 21 °C (Table 4).

Apart from petunia, neither air ADT nor RZH temperature influenced stem caliper of rooted cuttings (Table 3). Generally, an increase in stem caliper is associated with an increase in DLI during both propagation and finish. For instance, the stem caliper of angelonia ‘AngelMist White Cloud’, argyranthemum ‘Madeira Cherry Red’, diascia ‘Wink Coral’, nemesia ‘Aromatica Royal’, osteospermum ‘Voltage Yellow’, and verbena ‘Aztec Violet’ cuttings increased as DLI increased from 1.2 to 12.3 $mol \cdot m^{-2} \cdot d^{-1}$ (Currey et al., 2012). The lack of a response in this study was not surprising, since the DLI was ≈10 to 13 $mol \cdot m^{-2} \cdot d^{-1}$ across all treatments.

Air ADT and RZH temperature interacted and influenced SDM of calibrachoa, petunia, and phlox. The highest SDM for phlox was observed at air ADT and RZH temperatures of 16 and 21 °C, respectively, as well as air and RZH temperatures of 21 and 27 °C, respectively (Table 5). However, no trend was observed for petunia and calibrachoa. This contrasts with previous studies where plants were harvested at first open flower or marketability and found a general decline in SDM as RZH and/or air temperature increased. For instance, SDM of petunia ‘Supertunia Red’, ‘Supertunia Bordeaux’, ‘Potunia Plus Red’, and recombinant inbred lines IA160 and IA349 decreased up to 43%, 43%, 25%, 44%, and 60%, respectively, when grown at an air ADT of 15 °C and increasing RZH temperatures from 21 to 27 °C (Olberg and Lopez, 2017) and as air ADT increased from 14 to 23 °C, SDM decreased by 25% for finished osteospermum ‘Asti Purple’ (Vaid et al., 2014). The differing SDM results between the current study and previous flowering studies could be largely due to developmental differences as SDM was recorded at 14 d as opposed to at first open flower.

A high root volume is necessary for adequate uptake of water and nutrients as well as successful establishment of a young plant. A rooted cutting that does not have a well-established root system is of poor quality and could delay shipping, transplant, and growth of the finished product. Previous propagation studies with increasing RZH temperatures reported an increase of root growth such as root length, number of roots, and more commonly dry mass (Gislerød, 1983; Wilkerson et al., 2005). For instance, poinsettia ‘Freedom Dark Red’ cuttings produced an average of 27 roots per cutting at an air ADT of 24 °C and RZH temperature of 27 °C compared to no root growth at an RZH temperature of 19 °C (Wilkerson et al., 2005). Poinsettia ‘Freedom Dark Red’ and ‘Lady’ cuttings had increasing root length as RZH temperature increased from ≈21 to 28 °C (Gislerød, 1983; Wilkerson et al., 2005). In this study, root growth was assessed by determining RDM, the R:S, and liner pullability. The RDM and R:S of petunia was greatest under an air ADT of 21 °C and RZH set point of 21 °C (Table 5). Although not significant, pullability of petunia was lower at these air and RZH temperatures. Osteospermum had similar trends with RDM and R:S to petunia at an air and RZH temperature of 21 °C, but liner pullability was significantly greater under these conditions (Tables 5 and 6). Similar to our findings, Gerovac (2014) reported a 53% decrease in RDM for osteospermum ‘Serenity Bronze’ at finish when air ADT was 16 °C and RZH was initiated 10 d after transplant to 21 °C compared to an air temperature of 20/18 °C (day/night) without RZH. In contrast, the RDM of osteospermum ‘Serenity Bronze’ was more than 50% greater at an air ADT of 16 °C and when 21 °C RZH was initiated directly upon transplant, compared to plants at an air day/night temperature of 20/18 °C without RZH (Gerovac, 2014).

Root dry mass of petunia was lowest at an air and RZH temperature of 21 and 27 °C, respectively, but increased at the lower air and RZH temperatures (Table 5). Previous RZH studies on other cold-tolerant crops have reported similar findings at both high and low RZH set points. For example, rooted cuttings of chrysanthemum ‘Horim’ developed poor root growth at an air ADT and RZH set point of 18 °C and 6 °C, respectively, compared to air ADT and RZH temperatures of 18 °C following 14 d after transplant (Mortensen, 1982). Additionally, Mortensen (1982) reported that chrysanthemum ‘Horim’ grown at RZH temperatures of 22 and 26 °C had thin, brown roots suggesting that adequate root growth must occur at air and RZH temperatures of 18 °C (Mortensen, 1982). Owen (2017) also reported that RDM of coral bells ‘Black Beauty’ propagated at an air ADT of 21 °C and RZH temperatures of 20, 24, and 28 °C declined as RZH temperature increased 14 d after transplant. Furthermore, RDM of pansy ‘Matrix Yellow’ (*Viola ×wittrockiana*) was 45% to 80% greater at an air ADT of 16 °C without RZH compared to an air temperature of 20/18 °C (day/night) without RZH and an air ADT of 16 °C with RZH set points ranging from 18 to 27 °C (Gerovac, 2014).

As air ADT increased and RZH temperature decreased, the R:S of petunia (prostrate growth) and osteospermum (vertical growth) declined, (Table 3 and 5). At an RZH set point of 27 °C, the R:S of petunia was 68% greater at an air ADT of 16 °C compared to 21 °C (Table 5). However, the opposite occurred for osteospermum at an RZH set point of 21 °C where the R:S was 57% greater at an air ADT of 21 °C compared to 16 °C. Wilkerson et al. (2005) reported that high RZH temperatures can negatively impact root growth for poinsettia ‘Freedom Dark Red’. Therefore, we hypothesize that RZH temperatures of 27 °C and 21 °C were deleterious for both petunia and osteospermum, respectively, resulting in less root growth at an air ADT 21 and 16 °C, respectively (Table 5).

Although reductions in the RDM and R:S of osteospermum were observed with decreasing air and RZH temperatures, liner pullability of osteospermum was negatively impacted at low and high RZH temperatures (Table 3). At the two temperature extremes, liner pullability was ≤50% for osteospermum compared to 80% and 90% at air temperatures of 16 and 21 °C, respectively, with an RZH set point of 24 °C (Table 6). Additionally, visible flower buds and flowers on calibrachoa were significantly affected by air ADT, with the greatest percentage at an air ADT of 21 °C (Table 6). However, visible flower buds and flowers were also recorded for osteospermum and petunia at time of harvest, but the interaction of air and RZH temperature had no significant (Table 3). This may be due to the possibility that the stock plants which the cuttings originated from had already initiated flower buds and we did not use any plant growth regulators to ensure other variables would not impact the outcome of the study.

Overall liner quality can be assessed by the QI, an integrated and quantitative method to determine plant growth responses to environmental conditions. Typically, the larger the QI value, the greater the quality of the young plant (Currey et al., 2013). To our knowledge, no research has investigated how the QI of cuttings is influenced by air and RZH temperature combinations. The interaction of air and RZH temperature only influenced the QI of the perennials: campanula, nepeta, and phlox, and none of the annuals investigated (Table 3). The highest QI of campanula, nepeta, and phlox occurred at air and RZH temperatures of 16 and 27 °C, 21 and 27 °C, and 16 and 21 °C, respectively (Table 4). However, no consistent trends can be made with the QI due to little interaction or individual effects of air ADT and RZH. Additionally, previous studies have reported similar plant qualities with or without RZH (Nisen et al., 1978; Sachs et al., 1992; Vogelezang, 1988). Similarly, the air ADT and RZH temperature did not influence the QI of osteospermum or rosemary, suggesting that it may be possible to propagate these genera at low air ADT with RZH (Tables 3 and 4).

The purpose of this study was to determine if cold-tolerant crops could be propagated at low air ADT and with RZH to provide a cost-effective method for greenhouse growers to save on energy costs during the winter months. Our findings indicate that air and RZH temperatures have less of an impact on stem caliper, RDM, and SDM, than previously hypothesized. Air and RZH temperature set points are also genera dependent and may even be cultivar dependent. For example, T_b of petunia 'Bravo Blue' and 'Dreams Neon Rose' were calculated to be 2.6 and 2.8 °C, respectively, whereas 'Single Frost' and 'Wave Purple' both had a T_b of 5.5 °C, implying that petunia cultivars are both cold-tolerant and cold-intermediate plants (Blanchard and Runkle, 2011b; Vaid and Runkle, 2013). In addition, we did not have a control without RZH to compare our findings to, which would have given us a better insight on the use of RZH during propagation.

Along with energy savings, Gerovac (2014) reported only a slight savings in the reduction of air ADT to 16 °C compared to a (day/night) control of 20/18 °C. Although a grower may save on energy costs by reducing the air ADT, the cost of keeping plants in the greenhouse increases, which negates the impact of reducing the temperature. In central Florida, Bodnaruk (1983) reported an increase in energy use of 30% when using RZH of 21 °C and air temperatures of 12 to 16 °C compared to no RZH, which cost an additional 10 cents per plant (assuming eight 82-cm plants per m^2). However, faster root growth of prayer plant (*Maranta leuconeura*), lucky bamboo (*Dracaena sanderiana*), Chinese evergreen (*Aglaonema commutatum*), and Ti plant 'Baby Doll' (*Cordyline terminalis*) occurred with RZH, which allowed plants to be sold quickly and additional cycles could be produced in the greenhouse to increase net profits (Bodnaruk, 1983).

Conclusion

Although this study identified differences amongst air and RZH temperatures during propagation of cold-tolerant plants, there were no clear trends to suggest that cold-tolerant crops might benefit from low air temperatures with RZH. However, it is apparent that the temperature extremes in this study of air and RZH temperatures of 16 and 21 °C as well as 21 and 27 °C, respectively, may have deleterious effects for certain genera and should be avoided. When taking all measurements into account, liners of calibrachoa, nemesia, nepeta, and osteospermum may benefit from propagation air and RZH temperatures of 16 and 24 °C, respectively. Whereas campanula, petunia, and phlox can be successfully propagated at air ADT of 16 or 21 °C and RZH set points of 21 and 27 °C, respectively. Additionally, due to poor rooting of rosemary, it is difficult to pinpoint adequate propagation air and RZH temperatures without extending the length of time of propagation and should be reassessed. Further research on T_b, T_{opt}, and T_{max} RZH temperatures during propagation should be established for economically important cold-tolerant crops. However, this research has established that cold-tolerant crops such as calibrachoa, campanula, nemesia, nepeta, osteospermum, petunia, and phlox may be propagated at lower air temperatures in combination with RZH without sacrificing plant quality or increasing propagation time but these results may be cultivar dependent.

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APPENDIX

Table II-1. Averages (mean ± SD) of air, tissue, and root-zone temperature, daily light integral (DLI), and vapor pressure deficit (VPD) during the 6 d of callusing for all experiments.

	Temperature (°C)			DLI	VPD
Date	Air	Plant[z]	Root-zone[z]	($mol \cdot m^{-2} \cdot d^{-1}$)	(kPa)
Oct. 2017	21.6 ± 0.5	23.9 ± 0.8	24.1 ± 0.3	5.8 ± 0.6	0.29
Nov. 2017	21.1 ± 1.0	24.6 ± 1.4	24.0 ± 0.8	5.6 ± 0.9	0.24
Jan. 2018	20.6 ± 0.8	23.7 ± 1.2	23.8 ± 0.4	5.2 ± 0.6	0.24
Nov. 2018	21.1 ± 0.8	24.2 ± 1.1	23.5 ± 1.7	5.3 ± 0.7	0.29
Jan. 2019	21.0 ± 1.1	22.0 ± 1.1	24.3 ± 0.4	4.9 ± 0.3	0.32
Feb. 2019	21.9 ± 1.2	23.8 ± 0.8	23.9 ± 0.8	5.0 ± 0.6	0.28

[z]Averaged across two benches.

Table II-2. Averages (mean ± SD) of air, tissue, and root-zone temperature, daily light integral (DLI), and vapor pressure deficit (VPD) during the 14 d of root-zone heating treatments for all experiments.

	Temperature (°C)					DLI	VPD
	Air	Plant[z]	Root-zone				
Date	16 21		21	24	27	($mol \cdot m^{-2} \cdot d^{-1}$)	(kPa)
Oct. 2017	15.9 ± 1.2	18.9 ± 3.8	20.6 ± 0.5	23.4 ± 1.0	26.1 ± 1.4	10.6 ± 2.4	0.25
	21.5 ± 0.9	24.3 ± 2.1	21.3 ± 1.2	23.7 ± 1.0	26.4 ± 1.1	11.5 ± 3.5	0.26
Nov. 2017	15.9 ± 1.5	19.7 ± 4.2	20.1 ± 1.3	23.3 ± 1.3	26.1 ± 1.8	10.0 ± 1.6	0.29
	21.0 ± 1.1	24.5 ± 2.0	21.0 ± 1.8	23.5 ± 0.9	26.6 ± 0.6	10.6 ± 2.1	0.29
Jan. 2018	14.8 ± 0.8	18.6 ± 2.2	20.6 ± 1.5	23.1 ± 1.1	26.1 ± 1.6	10.0 ± 1.9	0.33
	21.1 ± 1.3	23.7 ± 1.8	21.8 ± 0.7	23.3 ± 1.0	26.7 ± 0.4	10.6 ± 2.2	0.30
Nov. 2018	16.4 ± 1.3	19.0 ± 3.7	21.5 ± 1.4	23.2 ± 2.3	26.4 ± 1.6	11.7 ± 1.2	0.33
	21.1 ± 1.3	24.2 ± 2.1	21.8 ± 0.7	23.3 ± 1.0	26.7 ± 0.4	10.8 ± 1.1	0.30
Jan. 2019	15.7 ± 1.9	18.9 ± 3.6	21.4 ± 2.9	24.3 ± 2.0	28.1 ± 3.1	11.0 ± 0.7	0.29
	20.9 ± 0.7	23.8 ± 2.0	21.2 ± 1.4	23.8 ± 1.5	26.9 ± 2.9	11.3 ± 0.6	0.34
Feb. 2019	16.2 ± 1.8	19.1 ± 2.5	21.2 ± 1.1	23.3 ± 2.0	26.9 ± 2.4	11.8 ± 0.4	0.32
	21.8 ± 1.0	24.0 ± 1.9	21.0 ± 1.7	24.3 ± 1.7	27.0 ± 1.1	11.8 ± 0.3	0.35

[z]Averaged across three benches.

Table II-3. Analyses of variance for the effects of air average daily temperature (ADT), root-zone heat (RZH), and their interaction during rooting of eight herbaceous cuttings on stem length, stem caliper, root dry mass, shoot dry mass, root-to-shoot ratio, quality index, liner pullability, and visible flower bud.

	Stem length (cm)	Stem caliper (mm)	Quality index	Root dry mass (mg)	Shoot dry mass (mg)	Root-to-shoot ratio	Liner pullability (%)	Visible flower bud (%)
				Calibrachoa				
ADT	***[z]	NS	***	NS	***	***	NS	**
RZH	***	NS	NS	***	NS	NS	NS	NS
ADT×RZH	NS	NS	NS	NS	*	NS	NS	NS
				Campanula				
ADT	NS	NS	NS	*	NS	NS	–[y]	–
RZH	NS	NS	NS	NS	NS	NS	–	–
ADT×RZH	***	NS	***	NS	NS	NS	–	–
				Nemesia				
ADT	***	NS	***	NS	***	***	–	–
RZH	***	NS	***	***	***	***	–	–
ADT×RZH	NS	NS	NS	NS	NS	NS	–	–
				Nepeta				
ADT	***	NS	***	*	***	***	–	–
RZH	***	NS	***	NS	***	***	–	–
ADT×RZH	**	NS	***	NS	NS	NS	–	–
				Osteospermum				
ADT	NS	NS	NS	NS	NS	*	NS	NS
RZH	NS	NS	NS	NS	NS	**	NS	NS
ADT×RZH	NS	NS	NS	*	NS	*	*	NS
				Petunia				
ADT	*	NS	NS	NS	NS	NS	NS	NS
RZH	**	**	*	NS	*	NS	NS	NS
ADT×RZH	*	*	NS	***	*	***	NS	NS
				Phlox				
ADT	*	NS	*	NS	NS	NS	–	–
RZH	***	NS	NS	NS	NS	NS	–	–
ADT×RZH	*	NS	***	NS	***	NS	–	–
				Rosemary				
ADT	***	NS	NS	**	NS	*	NS	NS
RZH	**	NS	NS	***	*	**	NS	NS
ADT×RZH	**	NS	NS	NS	NS	NS	NS	NS

[z]NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.
[y]No data were collected.

Table II-4. Stem length and quality index [total dry mass × (root-to-shoot ratio + sturdiness quotient)] for eight herbaceous cuttings. All genera were propagated at an average daily air temperature of 16 and 21 °C and root-zone temperature set points of 21, 24, and 27 °C for 28 d.

Air temperature (°C)	Stem length (cm)			Quality index		
	Root-zone temperature (°C)					
	21	24	27	21	24	27
				Calibrachoa		
16	7.0aA	7.2aA	7.3aB	900.9aA	930.8aA	840.2aB
21	7.6bA	7.8bA	8.8aA	1084.3aA	1055.9aA	1188.5aA
				Campanula		
16	2.7bA	3.0abA	3.5aA	108.3bB	147.5aA	164.3aA
21	3.1aA	3.0aA	2.8aB	154.2aA	145.4aA	140.0aA
				Nemesia		
16	7.0bB	7.6abB	8.1aB	477.2aB	591.2aB	559.5aB
21	11.1bA	12.0aA	12.5aA	913.3bA	1139.6aA	1105.9aA
				Nepeta		
16	6.7bB	6.6bB	7.5aB	635.3aB	609.1aB	719.8aB
21	9.2bA	9.4bA	11.2aA	877.4bA	972.7bA	1316.7aA
				Osteospermum		
16	8.4	9.0	9.3	534.1	678.8	625.9
21	9.0	8.9	8.7	618.3	624.9	598.6
				Petunia		
16	5.8bA	6.3aA	5.9abA	592.3	652.7	652.7
21	5.5bA	5.8abB	6.1aA	565.6	610.5	665.2
				Phlox		
16	4.7aA	4.7aA	4.1bA	628.0aA	594.7aA	456.7bA
21	4.0bB	4.6aA	4.0bA	464.3aB	502.7aA	566.8aA
				Rosemary		
16	6.2aA	6.3aA	6.3aB	613.6	672.6	648.6
21	6.4bA	6.7bA	7.3aA	612.0	663.4	663.6

[z]Within-row means followed by different lowercase letters are significantly different according to Tukey's honest significant difference (HSD) test at $P \leq 0.05$.
[y]Within-column means followed by different uppercase letters are significantly different according to Tukey's HSD test at $P \leq 0.05$.

Table II-5. Root dry mass, shoot dry mass, and root-to-shoot ratio of eight herbaceous cuttings. All genera were propagated at an average daily air temperature of 16 and 21 °C and root-zone temperature set points of 21, 24, and 27 °C for 28 d.

Air temperature (°C)	Root dry mass (mg)			Shoot dry mass (mg)			Root-to-shoot ratio		
	Root-zone temperature (°C)								
	21	24	27	21	24	27	21	24	27
				Calibrachoa					
16	35.3aA	33.7abA	28.9bA	128.1abA	134.4aA	110.4bB	0.28aA	0.25aA	0.27aA
21	37.5aA	33.5abA	31.0bA	149.0aA	142.4aA	145.4aA	0.25aA	0.24aA	0.22aB
				Campanula					
16	11.1	14.2	14.5	55.9	66.9	70.5	0.23	0.23	0.23
21	15.2	15.1	15.7	69.1	71.3	60.7	0.24	0.22	0.28
				Nemesia					
16	25.7abA	28.1aA	20.6bA	66.5bB	84.0aB	71.0bB	0.39aA	0.34abA	0.29bA
21	28.4aA	28.1aA	22.0bA	83.8bA	104.0aA	100.1aA	0.35aA	0.28bA	0.22bB
				Nepeta					
16	45.6	42.8	45.7	94.2bB	100.3abB	115.7aB	0.52aB	0.44bA	0.40bA
21	46.3	49.0	52.1	118.2bA	121.6bA	151.8aA	0.40aA	0.40aA	0.35aA
				Osteospermum					
16	19.0bB	33.7aA	29.5abA	142.2	144.7	136.9	0.14bB	0.23aA	0.22aA
21	33.0aA	32.2aA	31.1aA	148.6	136.7	142.0	0.22aA	0.24aA	0.23aA
				Petunia					
16	41.4aA	42.8aA	49.7aA	141.7abA	165.4aA	137.7bA	0.30abA	0.26bA	0.38aA
21	51.2aA	45.0abA	37.3bB	131.4aA	141.7aA	145.4aA	0.39aA	0.33abA	0.26bB
				Phlox					
16	38.0	43.4	34.3	298.1aA	261.0abA	228.1bB	0.14	0.17	0.15
21	37.8	43.8	41.1	234.3bB	226.1bA	282.5aA	0.17	0.20	0.16
				Rosemary					
16	24.6bA	34.6aB	27.3bA	121.7abA	131.9aA	115.1bA	0.21bA	0.26aA	0.24abA
21	23.5aA	27.4aA	24.4aA	122.9aA	121.7aA	119.0aA	0.20aA	0.23aA	0.20aA

[z]Within-row means followed by different lowercase letters are significantly different according to Tukey's HSD test at $P \leq 0.05$.
[y]Within-column means followed by different uppercase letters are significantly different according to Tukey's HSD test at $P \leq 0.05$.

Table II-6. Liner pullability and visible flower bud percentage of four herbaceous stem cuttings. All genera were propagated at an average daily air temperature of 16 and 21 °C and root-zone temperature set points of 21, 24, and 27 °C for 28 d.

Air temperature (°C)	Liner pullability (%)			Visible flower bud (%)		
	Root-zone temperature (°C)					
	21	24	27	21	24	27
				Calibrachoa		
16	50	80	75	40a[z]B[y]	35aA	65aA
21	65	80	90	90aA	60aA	65aA
				Osteospermum		
16	10bB	80aA	70aA	20	20	20
21	80aA	90aA	50aA	20	10	20
				Petunia		
16	95	90	85	95	100	100
21	65	75	70	100	100	100
				Rosemary		
16	40	30	40	0	0	0
21	45	50	40	0	0	0

[z]Within-row means followed by different lowercase letters are significantly different according to Tukey's HSD test at $P \leq 0.05$.
[y]Within-column means followed by different uppercase letters are significantly different according to Tukey's HSD test at $P \leq 0.05$.

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SECTION III

DURATION OF LIGHT-EMITTING DIODE (LED) SUPPLEMENTAL LIGHTING PROVIDING FAR-RED RADIATION DURING SEEDLING PRODUCTION INFLUENCES SUBSEQUENT TIME TO FLOWER OF LONG-DAY ANNUALS

Duration of light-emitting diode (LED) supplemental lighting providing far-red radiation during seedling production influences subsequent time to flower of long-day annuals

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Abstract

A low red (R) to far-red (FR) radiation ratio can hasten or elicit a flowering response in many long-day plants (LDPs). However, the majority of light-emitting diode (LED) supplemental lighting (SL) fixtures on the market only contain blue (B) and R LEDs and thus, flowering of some LDPs may be delayed if FR radiation is not included in the spectrum. The objectives of this study were to determine 1) the minimum duration of FR radiation needed at the seedling stage to promote subsequent flowering of LDPs and 2) to quantify the response of a day-neutral plant to the addition of FR radiation. Upon germination, seedlings of calibrachoa ‘Kabloom Light Pink Blast’ or ‘Kabloom Pink Blast’ (*Calibrachoa* ×*hybrida*), impatiens ‘Accent Premium Red’ (*Impatiens walleriana*), petunia ‘Wave Carmine Velour’ (*Petunia* ×*hybrida*), and snapdragon ‘Liberty Yellow Classic’ (*Antirrhinum majus*), were placed under lighting treatments that included a 9-h truncated short day (SD) or five SL treatments delivering a total photon flux density (*TPFD*) of 70 μmol·m^{-2}·s^{-1} for up to 16 h·d^{-1} based on an instantaneous threshold. The LED SL treatments defined by their wavebands (*TPFD* in μmol·m^{-2}·s^{-1}) of B (400–500 nm) and R (600–700 nm) radiation with or without FR (700–800 nm) radiation were $B_{15}R_{40}FR_{15}$ or $B_{20}R_{50}$. After 14 or 21 d under $B_{20}R_{50}$ LED SL, randomly selected seedlings were transferred to $B_{15}R_{40}FR_{15}$ LED SL where they stayed for the remainder of the experiment. The duration of replication (Rep.) 1 was 35 d and 28 d for Rep. 2 and 3. Thus, the treatments were 9-h SD, HPS SL (35 or 28 d), $B_{20}R_{50}$ (35 or 28 d), $B_{20}R_{50}$ (21 d) + $B_{15}R_{40}FR_{15}$ (14 or 7 d), $B_{20}R_{50}$ (14 d) + $B_{15}R_{40}FR_{15}$ (21 or 14 d), and $B_{15}R_{40}FR_{15}$ LED SL (35 or 28 d). For Rep. 1, calibrachoa and petunia seedlings were up to 52% and 158% taller, respectively, under $B_{20}R_{50}$ (21 d) + $B_{15}R_{40}FR_{15}$ SL (14 d) compared to other SL treatments. The root dry mass (RDM) of calibrachoa and petunia was 53%–82% and 22%–36% greater, respectively, under HPS SL than LED SL.

However, in Rep. 2 and 3, petunia stem length was not influenced by lighting treatment whereas snapdragon was 17% taller under $B_{20}R_{50}$ (21 or 14 d) + $B_{15}R_{40}FR_{15}$ SL (7 or 14 d) and HPS SL (28 d) compared to $B_{15}R_{40}FR_{15}$ SL (28 d). Additionally, the RDM for snapdragon was up to 33% and 22% lower under $B_{20}R_{50}$ (14 d) + $B_{15}R_{40}FR_{15}$ SL (14 d) or $B_{15}R_{40}FR_{15}$ SL (28 d), respectively, compared to all other treatments. Time to first visible bud and flower was hastened by the duration of FR radiation by up to 7, 4, and 8 d for calibrachoa, petunia (Rep. 1), and snapdragon, respectively. Our results indicate that inclusion of FR radiation via LED SL provided for at least 14 d at the end of the seedling stage can hasten time to flower of LDPs without excessive stem elongation at flower.

Keywords: *Antirrhinum majus*, *Calibrachoa ×hybrida*, daily light integral, *Impatiens walleriana*, *Petunia ×hybrida*, red to far-red ratio

Abbreviations: ADT, average daily temperature; B, blue radiation; DLI, daily light integral; DNP, day-neutral plant; FR, far-red radiation; G, green radiation; GI, growth index; HPS, high-pressure sodium; LAI, leaf area index; LED, light-emitting diode; LDP, long-day plant; LMA, leaf mass per area; *PPFD*, photosynthetic photon flux density; QI, quality index; R, red radiation; RDM, root dry mass; R:S, root-to-shoot ratio; R:FR, red to far-red radiation ratio; SD, short day; SDM, shoot dry mass; SDP, short-day plant; SL, supplemental lighting; SSL, sole-source lighting; SQ, sturdiness quotient; TDM, total dry mass; *TPFD*, total photon flux density; VPD, vapor-pressure deficit

Introduction

Peak young ornamental plant propagation occurs from late winter to early spring coinciding with low solar radiation intensities (Styer, 2011). In greenhouses located in Northern latitudes, the photosynthetic daily light integral (DLI) can be as low as 2 $mol \cdot m^{-2} \cdot d^{-1}$ during short and overcast days (Faust, 2011). This is well below the 10 to 12 $mol \cdot m^{-2} \cdot d^{-1}$ recommended for young plant production (Faust, 2011; Lopez and Runkle, 2008; Pramuk and Runkle, 2005).

Supplemental lighting (SL) can be used during young plant production to increase the DLI in greenhouses (Faust, 2011; Styer, 2011). High-pressure sodium (HPS) lamps have been the industry standard for greenhouse production because of their costs and longevity while primarily emitting wavelengths of yellow (565–590 nm), orange (590–625 nm), and red (625–700 nm) radiation with a small proportion of far-red (FR, 700–800 nm) radiation (Spaargaren, 2001). In recent years, high-intensity light-emitting diode (LED) fixtures for horticultural applications have gained popularity for use as SL due to the high efficacy and long lifespan of LEDs (Bourget, 2008; Stober et al., 2017). LEDs are solid-state semiconductors that can emit radiation within a narrow spectrum (Bourget, 2008). Generally, commercial LED SL fixtures provide a mixture of blue (B) and R radiation, with some fixtures also providing white, and/or FR radiation. As of 2017, it was estimated that only 2% of greenhouses in the U.S. have installed LED fixtures for SL; however, this number is steadily increasing as operations are replacing HPS lamps (Stober et al., 2017).

Plant growth is highly dependent on the availability of B (400–500 nm), green (G, 500–600 nm), and R (600–700 nm) radiation, known as photosynthetic active radiation (PAR) (Runkle, 2006) as well as FR (700–800 nm) radiation (Lopez et al., 2017). Plants absorb light through photoreceptors such as cryptochrome (B and UV-A radiation) and phytochrome (R, FR, and some B radiation) to control numerous developmental processes. The two forms of phytochrome; the R (P_r) and FR (P_{fr}) absorbing forms, as well as the R to FR radiation ratio (R:FR) controls seed germination, flowering, and stem elongation of plants (Heins et al., 2000; Thomas and Vince-Prue, 1997). For example, with a low R:FR, P_r is converted to P_{fr} which promotes flowering in long-day plants (LDPs) but inhibits flowering of short-day plants (SDPs) and can also induce the shade-avoidance response (Heins et al., 2000; Runkle and Heins, 2001; Thomas and Vince-Prue, 1997).

With many LED fixtures on the market only emitting B and R radiation, the likelihood of a plant receiving sufficient FR radiation from solar radiation is low under short day (SD) conditions and can potentially delay flowering of LDPs. The addition of FR radiation to SL LED fixtures has become a growing interest as many LDPs need a low R:FR for rapid flower initiation (Craig and Runkle, 2012; Runkle and Heins, 2001). For instance, subsequent time to flower of snapdragon 'Trailing Candy Showers Yellow' (*Antirrhinum majus*) seedlings under LED sole-source lighting (SSL) providing 16 to 64 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of FR radiation was hastened by at least 10 d compared to seedlings under 32 and 128 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of B and R radiation, respectively (Park and Runkle, 2017). Similarly, Poel and Runkle (2017b) reported an 8 d reduction in subsequent time to flower for snapdragon 'Montego Yellow' seedlings grown under $B_{12}G_{20}R_{68}FR_{12}$ LED SL (providing 12 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of FR radiation) compared to seedlings under LED SL without FR radiation. However, time to flower was not different for seedlings under HPS SL providing the same photosynthetic photon flux density (*PPFD*) of 90 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Additionally, subsequent time to flower of pansy 'Matrix Yellow' (*Viola ×wittrockiana*) and petunia 'Purple Wave' (*Petunia ×hybrida*) seedlings grown under LED SSL providing proportions (%) of $B_9R_{84}FR_7$ was hastened by 7 and 2 d, respectively, compared to seedlings under $B_{13}R_{87}$ (Craver et al., 2018).

In many of these studies, seedling stem elongation increased with the addition of FR radiation, but the effects were genera-dependent. After 30 to 37 d, stem length of geranium 'Pinto Premium Orange Bicolor' (*Pelargonium ×hortorum*), impatiens 'Super Elfin XP Red' (*Impatiens walleriana*), petunia 'Wave Blue', and snapdragon 'Trailing Candy Showers Yellow' seedlings were 41%, 24%, 95%, and 41% shorter, respectively, under LED SSL providing $B_{32}R_{128}$ compared to all other treatments containing FR radiation. The tallest seedlings were those grown under LED SSL providing $B_{32}R_{64}FR_{64}$ radiation (Park and Runkle, 2017). Similarly, snapdragon 'Montego Yellow' seedlings grown under LED SL providing $B_{12}G_{20}R_{68}FR_{12}$ radiation were the tallest compared to all other SL treatments. In contrast, pepper 'Long Red Slim Cayenne' (*Capsicum annuum*), tomato 'Supersweet' (*Solanum lycopersicum*), or petunia 'Single Dreams White' did not exhibit significant stem elongation from the addition of FR radiation (Poel and Runkle, 2017b).

It has been established that FR radiation in combination with R radiation is an underlying factor in flower initiation in most LDPs (Craig and Runkle, 2012). However, no research to our knowledge has determined the duration that a seedling must be exposed to both R and FR radiation to hasten subsequent time to flower of LDPs. Therefore, our objective was to 1) quantify the minimum duration a seedling needs to be exposed to FR radiation to induce subsequent flowering of LDPs and 2) determine if day neutral plants (DNPs) are negatively influenced by the addition of FR radiation.

Materials and methods

Plant material

Seeds of calibrachoa ‘Kabloom Light Pink Blast’ [replication (Rep.) 1 and 3] and ‘Kabloom Pink Blast’ (Rep. 2) (*Calibrachoa ×hybrida*), petunia ‘Wave Carmine Velour’ (PanAmerican Seed Co., West Chicago, IL), impatiens ‘Accent Premium Red’, and snapdragon ‘Liberty Classic Yellow’ (Rep. 2 and 3) (Syngenta Flowers LLC., Gilroy, CA) were sown in 162-cell (16.9-mL individual cell volume) trays (PL-162; T.O. Plastics, Clearwater, MN) at a commercial greenhouse (Raker-Roberta’s Young Plants, Litchfield, MI) and were delivered upon germination on 25 Feb. 2019, 18 Nov. 2019, and 14 Jan. 2020. Each tray was divided in half to represent two blocks per genera and each was assigned to six lighting treatments for a total of 35 (Rep. 1) or 28 d (Rep. 2 and 3).

Growing environment and lighting treatments

Four compartmentalized glass-glazed greenhouses at the Plant Science Research Greenhouse ranges at Michigan State University [(MSU), East Lansing, MI (lat. 43° N)] were used for the lighting treatments. To avoid radiation contamination from adjacent treatments, a thick coat of whitewash was applied to the glass between compartments. The five SL treatments provided a total photon flux density (*TPFD*) of 70 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 16 h based on an instantaneous threshold [on from 0600 to 2200 HR when the outside *TPFD* was below ≈440 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (on for a minimum of 25 minutes and off for a minimum of 20 minutes)]. A truncated 9-h SD (treatment 1; control) was created by pulling opaque black cloths over a bench at 1700 HR and opened at 0800 HR. SL was provided by 400-W HPS lamps (LR48877; P.L. Light Systems, Beamsville, ON, Canada) (treatment 2), LED fixtures providing B and R radiation (LumiGrow Pro 325; LumiGrow, Emeryville, CA) (treatment 3) and by LED fixtures providing B, R, and FR radiation (LumiGrow Pro 325; LumiGrow) (treatment 4). Treatments 5 and 6 were a combination of treatments 3 and 4 for varying durations (Table 1). Treatments 3 and 4 were delivered by B and R with or without FR LEDs and defined by their 100-nm wavebands (*TPFD* in μmol·m^{-2}·s^{-1}) of B (400–500 nm), R (600–700 nm), and FR (700–800 nm) radiation were $B_{20}R_{50}$ and $B_{15}R_{40}FR_{15}$, respectively. The HPS lamps emitted a *TPFD* of $B_{5}G_{38}R_{26}FR_{5}$. The total number of lamp hours of operation during each Rep. were 415 (Rep. 1), 446 (Rep. 2), and 428 h (Rep. 3). Trays in each greenhouse compartment were randomly re-positioned every third day to diminish any positional effects. The R:FR and estimated phytochrome photoequilibrium (PPE, PPE = P_{fr}/P_{r+fr}) were calculated for treatments 2 through 4 according to Sager et al. (1988) and are included in Table 1. For all treatments, spectral quality and radiation intensity at plant height were measured in 14 to 18 separate locations throughout the growing area with a portable spectroradiometer (LI-180; LI-COR Biosciences, Lincoln, NE) (Fig. 1). Spectral scans and radiation intensity measurements were taken at night, at the beginning of each Rep. to ensure consistency from one Rep. to another. The total DLIs (sunlight + SL) are reported in Table 2.

Each greenhouse compartment was equipped with an aspirated thermocouple (Omega Engineering, Stamford, CT), infrared sensor (Type T, OS36-01; Omega Engineering), and quantum sensor (LI-190R; LI-COR Biosciences) to record the air and plant temperature, and radiation intensity, respectively, and were logged to a data logger (CR1000; Campbell Scientific, Logan, UT) every 10 s and an average was accumulated every hour. The compartments had an average daily temperature (ADT) set point of 23 °C and a DLI of ≈9 and ≈13 mol·m^{-2}·d^{-1} (Rep. 1) and ≈3 and ≈8 mol·m^{-2}·d^{-1} (Rep. 2 and 3) for the 9-h SD and SL treatments, respectively (Table 2). Trays were placed on top of capillary mats and hand misted (Super Fine Fogg-It Nozzle; Fogg-It Nozzle Co. Inc., Belmont, CA) twice a day with reverse osmosis water containing a water-soluble fertilizer (MSU Plug Special 13N–2.2P–10.8K; Greencare Fertilizers, Inc., Kankakee, IL) and micronutrient supplement (M.O.S.T.; JR Peters, Inc., Allentown, PA) to deliver the following ($mg \cdot L^{-1}$): 60 N, 10 P, 50 K, 28 Ca, 5 Mg, 27 S, 16 Fe, 10 Zn, 17 Mn, 5 Cu, 3 B, and 0.2 Mo.

Common environment transition

After 35 (Rep. 1) or 28 d (Rep. 2 and 3), five plugs per species per treatment and block were transplanted into a common environment with an air ADT set point of 20 °C and under a 16-h photoperiod supplemented by HPS lamps [*TPFD* of 70 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at plant height as measured with a quantum sensor (LI-190R; LI-COR, Lincoln, NE)] and controlled as previously described (Table 3). Plugs of calibrachoa and impatiens were transplanted into 11-cm (600-mL) pots, 13-cm (770-mL) pots for snapdragon, and 15-cm (1.3-L) containers (The HC Companies, Twinsburg, OH) for petunia, filled with a commercial soilless substrate composed of 70% peat moss, 21% perlite, and 9% vermiculite (Suremix; Michigan Grower Products Inc., Galesburg, MI). Plants were hand irrigated when necessary with a water-soluble fertilizer (Orchid RO Water Special 13N–1.3P–12.5K; Greencare Fertilizers, Inc.) containing ($mg \cdot L^{-1}$): 125 N, 13 P, 121 K, 78 Ca, 19 Mg, 0.17 B, 0.43 Cu, 1.7 Fe, 0.85 Mn, 0.17 Mo, and 0.43 Zn.

Data collection

For Rep. 1, samples were harvested 7 d later than Rep. 2 and 3. Thus, on 01 Apr. 2019 (Rep. 1, 35 d), 16 Dec. 2019 (Rep. 2, 28 d), and 11 Feb. 2020 (Rep. 3, 28 d), five seedlings per genera per block and treatment were randomly selected and substrate was gently rinsed from the roots. Measurements were recorded for stem length, stem caliper, and leaf area (petunia only). Stem length was measured with a ruler from the base of the hypocotyl to the top of the shoot apical meristem. Stem caliper was measured from the base of the first true leaf with a digital caliper

(41101 DigiMax; Wiha Switzerland, Monticello, MN). A leaf area meter (LI-3100; LI-COR Biosciences) was used to calculate the total area (cm^2) of leaves that were removed from the axil for each petunia seedling. The leaf area was used to calculate the leaf area index (LAI) as the ratio of leaf area to individual cell surface area of a 162-cell tray (5.5 cm^2). At harvest, seedling stems, roots, and leaves were excised and dried separately in a forced air oven at 70 °C for 3 d. Stem, leaf, and root dry mass (RDM) was measured once the samples were dry. The shoot dry mass (SDM) was calculated as the sum of the stem and leaf dry mass. Seedling compactness ($mg \cdot mm^{-1}$) was calculated as the ratio of SDM to stem length at harvest. Leaf mass per area (LMA; $mg \cdot cm^{-2}$) was calculated as the ratio of leaf dry mass to leaf area at harvest. The total dry mass (TDM) was calculated as the sum of SDM and RDM and the root-to-shoot ratio (R:S) was calculated by dividing RDM by SDM. The sturdiness quotient [SQ; SQ = (stem length/stem caliper)] and quality index {QI; QI = [TDM × (R:S + SQ)]} (Currey et al., 2013) were also calculated to quantify the quality of the seedlings under each treatment.

Seedlings that were transplanted into a common growing environment were monitored daily to assess date of first visible flower bud and open flower, height of the main stem, plant width (perpendicular and parallel), number of lateral branches, total number of visible buds and flowers upon flowering, and length of longest shoot (petunia). The height and widths were used to calculate the growth index (GI; GI = height + [(width 1 + width 2)/2]/2) for each plant (Krug et al., 2010).

Experimental design and statistical analyses

The experiment was set up as a randomized complete block design and replicated twice over time. Lighting treatments were randomized across greenhouse compartments and each block of trays was randomly placed amongst the treatments. Due to DLI differences between Reps., Rep.

1 was analyzed separately and Rep. 2 and 3 were pooled. Data were analyzed using SAS (version 9.2; SAS Institute, Cary, NC) mixed model procedure (PROC MIXED) for analysis of variance (ANOVA). Means were separated using Fisher's least significant difference (LSD) test at $P \leq 0.05$.

Results

Seedlings

Stem length of calibrachoa, impatiens, petunia (Rep. 1 only), and snapdragon were influenced by SL treatments, and in some cases more so with SL providing FR radiation (Fig. 2A-D). For Rep. 1, calibrachoa and petunia seedlings grown under $B_{20}R_{50}$ (21 d) + $B_{15}R_{40}FR_{15}$ LED SL (14 d) were 27% and 52% taller than those under $B_{15}R_{40}FR_{15}$ LED SL (35 d) as well as 41% and 158% taller, respectively, than those under HPS SL for (35 d), respectively (Fig. 2A and C). In contrast, calibrachoa and snapdragon seedlings were taller under all SL treatments compared to those under a 9-h SD for 28 d in Rep. 2 and 3 (Fig. 2A-D). All SL treatments providing FR radiation for ≥14 d (Rep. 1) or $B_{15}R_{40}FR_{15}$ LED SL (28 d) (Rep. 2 and 3) resulted in taller impatiens compared to seedlings under $B_{20}R_{50}$ SL or 9-h SD for 28 or 35 d (Fig. 2B).

Stem caliper of calibrachoa (Rep. 2 and 3), impatiens, petunia, and snapdragon were influenced by all SL treatments (Fig. 2E-H). For Rep. 1, stem caliper of impatiens and petunia increased by 26%–38% and 49%–115%, respectively, under all SL for 35 d compared to 9-h SD for 35 d (Fig. 2F and G). Whereas, for Rep. 2 and 3, stem caliper of calibrachoa, impatiens, petunia, and snapdragon increased up to 63%, 59%, 79%, and 36%, respectively, when grown under SL treatments for 28 d compared to 9-h SD for 28 d (Fig. 2E-H). Seedling compactness is a quantitative measurement to assess overall seedling shoot compactness with higher values equaling higher seedling compactness. There were no consistent trends across Reps., genera, or lighting treatments (Fig. 2I-L). For example, seedlings of calibrachoa were compact under a 9-h SD, HPS SL, or $B_{20}R_{50}$ LED SL for 35 d, compared to other lighting treatments in Rep. 1 (Fig. 2I). However, in Rep. 2 and 3, seedlings were more compact under HPS SL or $B_{20}R_{50}$ LED SL for 28 d but was not different from $B_{15}R_{40}FR_{15}$ LED SL for 28 d (Fig. 2I).

Similar to seedling compactness, the SQ, which accounts for overall stem sturdiness, varied between Reps., genera, and lighting treatments, with the exception of petunia (Rep. 2 and 3) which was not influenced by lighting treatments (Fig. 2M-P). In Rep. 1, the SQ for calibrachoa and petunia was greatest under $B_{20}R_{50}$ (21 d) + $B_{15}R_{40}FR_{15}$ (14 d) LED SL and for petunia under $B_{20}R_{50}$ (14 d) + $B_{15}R_{40}FR_{15}$ (21 d) LED SL (Fig. 2N and O). For Rep. 2 and 3, the SQ of snapdragon grown under $B_{15}R_{40}FR_{15}$ LED SL for 28 d was 14% to 73% greater than all other treatments (Fig. 2P).

The RDM and SDM for calibrachoa, impatiens, petunia, and snapdragon were all influenced by SL treatments across Reps. (Fig. 3A-H). For instance, the RDM and SDM of calibrachoa, impatiens, and petunia were up to 340% and 199%, 128% and 84%, and 205% and 163% greater, respectively, under SL than a 9-h SD for 35 d during Rep. 1 (Fig. 3A-C, E-G). Similarly for Rep. 2 and 3, the RDM and SDM of calibrachoa, impatiens, petunia, and snapdragon increased up to 6.7- and 3.8-fold, 3.8- and 2.3-fold, 7.8- and 3.1-fold, and 10.4- and 5.2-fold, respectively, when grown under SL treatments compared to 9-h SD for 28 d (Fig. 3A-H). Furthermore, calibrachoa and petunia grown under HPS SL (35 d) had greater RDM by 53%–82% and 22%–36%, respectively, compared to LED SL treatments during Rep. 1 (Fig. 3A and C). In contrast, the RDM was greater under LED SL providing FR radiation for ≥7 d for calibrachoa or under HPS and $B_{15}R_{40}FR_{15}$ LED SL (28 d) for petunia during Rep. 2 and 3 (Fig. 3

A and C). For Rep. 2 and 3, the SDM of impatiens and petunia was greatest under HPS SL (28 d), which is different from Rep. 1 (Fig. 3F and G). The R:S was influenced by lighting treatments for all crops except for impatiens (Rep. 1), however it varied between Reps. (Fig. 3I-L). For Rep. 1, the R:S of calibrachoa and petunia was highest under HPS SL (35 d) but was only different from petunia seedlings under $B_{15}R_{40}FR_{15}$ SL (35 d) (Fig. 3I and K). In contrast, for Rep. 2 and 3, the R:S was greatest under LED SL providing FR radiation for ≥14 d for calibrachoa, or $B_{15}R_{40}FR_{15}$ LED SL for 28 d for petunia (Fig. 3I and K). Additionally, the R:S was greater among impatiens grown under all LED SL for 28 d (Fig. 3J). Furthermore, the R:S of snapdragon was 1.3-times greater under $B_{20}R_{50}$ LED SL (28 d) compared to $B_{20}R_{50}$ (14 d) + $B_{15}R_{40}FR_{15}$ LED SL (14 d) (Fig. 3L).

The QI for calibrachoa, impatiens, petunia, and snapdragon were influenced by SL treatments across Reps (Fig. 3M-P). For example, in Rep. 1, the QI for calibrachoa was 7.9- to 8.4-times greater under $B_{15}R_{40}FR_{15}$ SL for 14 to 21 d compared to $B_{20}R_{50}$ LED SL or 9-h SD for 35 d (Fig. 3M). Whereas for impatiens, the QI was greatest under HPS SL (35 d) and $B_{20}R_{50}$ (14 d) + $B_{15}R_{40}FR_{15}$ SL (21 d) but was not different from $B_{15}R_{40}FR_{15}$ SL (35 d) (Fig. 3N). In contrast, the QI of impatiens in Rep. 2 and 3 was greater under HPS SL and $B_{15}R_{40}FR_{15}$ SL (28 d) compared to $B_{20}R_{50}$ SL (28 d) (Fig. 3N). Furthermore, the QI of snapdragon increased by 60% when grown for 28 d under $B_{15}R_{40}FR_{15}$ SL compared to $B_{20}R_{50}$ SL (Fig. 3P).

For petunia, the leaf area, LMA, and LAI were variably influenced by lighting treatments across Reps. (Fig. 4A-C). For instance, during Rep. 1, the leaf area and LAI of petunia both increased by 21% when as $B_{15}R_{40}FR_{15}$ LED SL treatment increased from 14 to 35 d (Fig. 4A and C). The LMA of petunia was 19%-21% greater under HPS SL (35 d) compared to LED SL containing FR radiation (Fig. 4B). Whereas for Rep. 2 and 3, leaf area and LAI of petunia were both 24% greater when grown for 28 d under HPS SL compared to $B_{15}R_{40}FR_{15}$ SL (28 d) (Fig. 4A and C). When grown under $B_{15}R_{40}FR_{15}$ SL (28 d), LMA increased by 17% and 12% compared to seedlings under $B_{15}R_{40}FR_{15}$ SL for 7 and 14 d, respectively (Fig. 4B).

Finished plants

Subsequent time to visible flower bud was influenced by lighting treatments for calibrachoa, petunia (Rep. 1), and snapdragon, while having slight influence on impatiens (Fig. 5A-D). Furthermore, subsequent time to flower of calibrachoa, petunia (Rep. 1), and snapdragon were influenced by lighting treatments, whereas impatiens was not affected (Fig. 5E-H). For example, timing of calibrachoa visible buds and open flowers was hastened by 6 and 7 d, respectively, under $B_{20}R_{50}$ (21 d) + $B_{15}R_{40}FR_{15}$ LED SL (14 d) compared to HPS SL for 35 d (Fig. 5A and E). In contrast, time to visible bud was hastened up to 9 d under $B_{20}R_{50}$ LED SL (28 d) compared to 9-h SD for calibrachoa during Rep. 2 and 3 (Fig. 5A). Under $B_{15}R_{40}FR_{15}$ SL (7 d), time to flower of calibrachoa was reduced by ~3 d compared to all other SL treatments containing FR radiation and by 12 d compared to 9-h SD (Fig. 5E). For petunia, time to visible bud and flower decreased by 5 and 4 d, respectively, under $B_{15}R_{40}FR_{15}$ SL compared to seedlings grown under HPS SL (35 d) for Rep. 1 but was not influenced during Rep. 2 and 3 (Fig. 5C and G). Time to visible bud of snapdragon decreased by 3 and 4 d when seedlings were grown under $B_{15}R_{40}FR_{15}$ SL (28 d) compared to HPS SL and $B_{20}R_{50}$ SL, respectively (Fig. 5D). Additionally, subsequent time to flower of snapdragon was hastened by 20, 8, and 6 d when seedlings were grown under $B_{15}R_{40}FR_{15}$ SL (28 d), compared to seedlings under 9-h SD, HPS SL, or $B_{20}R_{50}$ SL for 28 d, respectively (Fig. 5H).

The number of visible flower buds and flowers at flowering was only influenced for Rep. 1 of calibrachoa and petunia, and Rep. 2 and 3 of snapdragon. At first open flower, calibrachoa and petunia had 20 and 17 fewer visible buds and flowers, respectively, when grown under $B_{20}R_{50}$ (21 d) + $B_{15}R_{40}FR_{15}$ SL (14 d) compared to HPS SL (35 d) (Fig. 5I and K). Whereas, snapdragon seedlings grown under LED SL containing FR radiation had 9 to 15 fewer visible buds and flowers compared to those propagated under HPS SL or $B_{20}R_{50}$ SL (28 d) (Fig. 5L).

Stem elongation was influenced by lighting treatments for petunia and snapdragon, whereas there was no effect for calibrachoa and impatiens (Fig. 6A-D). For example, the shoot length of petunia at first flowering was shorter under LED SL treatments containing 15 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of FR but was not significant from plants under HPS SL (35 d) (Fig. 6C). In contrast, petunia shoots at flower were 20% longer when seedlings were grown under $B_{15}R_{40}FR_{15}$ SL (28 d) compared to seedlings under HPS SL during Rep. 2 and 3 (Fig. 6C). For snapdragon, stem length decreased from 49.5 cm under HPS SL to 37.7 cm under $B_{15}R_{40}FR_{15}$ SL (Fig. 6D).

The GI was only influenced by lighting treatments for calibrachoa (Rep. 1) and snapdragon, while impatiens and petunia were not affected (Fig. 6E-H). For instance, the GI of calibrachoa decreased by ~20% when seedlings were grown under $B_{15}R_{40}FR_{15}$ SL for 21 to 35 d compared to seedlings grown under HPS SL (35 d) (Fig. 6E). Similarly, the GI of snapdragon decreased by 11% as duration of $B_{15}R_{40}FR_{15}$ SL increased from 7 to 28 d (Fig. 6H). Furthermore, lighting treatments influenced the number of lateral branches at first open flower for calibrachoa (Rep. 2 and 3) and snapdragon and did not influence impatiens or petunia (Fig. 6I-K). When grown under $B_{20}R_{50}$ SL (28 d) or $B_{15}R_{40}FR_{15}$ SL (14 to 28 d), the number of calibrachoa lateral branches decreased by 11%–14% compared to HPS SL (Fig. 6I). Under $B_{15}R_{40}FR_{15}$ SL (28 d), the number of snapdragon lateral branches was 32% and 36% lower compared to HPS and $B_{20}R_{50}$ SL (28 d), respectively (Fig. 6L).

Discussion

Seedlings

For young plant production, DLIs between 10 to 12 mol·m^{-2}·d^{-1} are recommended to promote adequate shoot and root growth of plugs and liners which can be achieved with HPS lamp or LED SL when greenhouse DLIs are low or SSL for indoor production (Currey and Lopez, 2013; Lopez and Runkle, 2008; Pramuk and Runkle, 2005; Owen and Lopez, 2018). The total DLI can be increased with SL; but with LED fixtures, the light quality can be manipulated to provide specific ratios of B, G, R, and FR radiation. Previous studies have found that HPS lamp and LED SL providing varying proportions of B, G, and/or R radiation can be substituted for one another due to little to no differences in plant morphology when the solar DLI is above ~7 mol·m^{-2}·d^{-1} (Currey and Lopez, 2015; Poel and Runkle, 2017a, 2017b; Randall and Lopez, 2014, 2015). However, research on FR radiation or R:FR outputs of LED SL has been minimally studied, especially for young plants.

In the current study, we found that both DLI and the duration that FR radiation is provided influenced seedling quality and subsequent time to flower of calibrachoa, petunia, and snapdragon. Not surprising, in Rep. 1, the stem length of calibrachoa and petunia seedlings were shorter under a 9-h SD, $B_{20}R_{50}$, and HPS lamp SL compared to LED SL providing FR radiation. In contrast, stem length and the SQ of calibrachoa and petunia decreased as the duration of LED SL providing FR radiation increased from 14 to 35 d (Fig. 2A and C). This was surprising because stem elongation is promoted under a low R:FR radiation ratio (<1:1) (Demotes-Mainard, 2016). In the current study the R:FR radiation ratios and PPEs were 5:1, 3:1, and 30:1 and 0.85, 0.80, and 0.87 under HPS lamps, $B_{15}R_{40}FR_{15}$, and $B_{20}R_{50}$ SL, respectively. Thus, we would expect that plants grown under $B_{20}R_{50}$ SL would be more compact than seedlings under HPS lamps or $B_{15}R_{40}FR_{15}$ SL. For example, the stem length of snapdragon seedlings decreased by 43% under $B_{20}R_{50}$ SL compared to those under $B_{15}R_{40}FR_{15}$ SL (Fig. 2D). Similar to our findings under $B_{15}R_{40}FR_{15}$ SL for ≥14 d (Fig. 2D), the tallest snapdragon 'Montego Yellow' seedlings were those under $B_{12}G_{20}R_{68}FR_{12}$ SL compared to all other HPS lamp and LED SL treatments without FR radiation (Poel and Runkle, 2017b). Furthermore, pepper 'Hungarian Wax' plants were up to 90% taller under a (ratio) 83:17 R:FR LED SL than under metal halide lamps, 100% R LEDs, or 99% R LEDs plus 1% B fluorescent lamps (Brown et al., 1995). Under SSL, Park and Runkle (2017) reported that seedlings of geranium 'Pinto Premium Orange Bicolor', impatiens 'Super Elfin XP Red', petunia 'Wave Blue', and snapdragon 'Trailing Candy Showers Yellow' were more compact as the PPE increased.

Previous studies have indicated that stem length generally decreases with increasing DLI (Blanchard et al., 2011; Fausey et al., 2005; Faust et al., 2005; Lopez and Runkle, 2008). However, in the current study, stem length of calibrachoa, impatiens, petunia (Rep. 1), and snapdragon generally increased under SL which provided a longer photoperiod and subsequently higher DLIs of 8 to 13 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ compared to seedlings under a 9-h SD with DLIs of 3 to 7 $mol{\cdot}m^{-2}{\cdot}d^{-1}$. Similarly, Poel and Runkle (2017a) reported that stems of snapdragon 'Montego Yellow' seedlings were ~40% to ~60% shorter under HPS lamps that provided a *PPFD* of 10 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ compared to SL providing 90 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$. In a separate study, the height of vinca 'Titan Dark Red' (*Catharanthus roseus*) decreased by 50%, as the DLI increased from ~6.5 to 10.5 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ whereas the height of impatiens 'Super Elfin XP Blue Pearl' was not affected by the DLI (Randall and Lopez, 2015). In the case of petunia (Rep. 2 and 3), the DLI may have been too low or the duration of SL may have been too short to see differences in stem length

(Fig. 2C). Additionally, petunia grows as a rosette, thus stem length measurements may not be applicable (Wollaeger and Runkle, 2014, 2015).

Stem length across all genera was generally reduced under $B_{20}R_{50}$ SL compared to all other SL treatments. Higher percentages of B radiation have been previously reported to reduce stem elongation in other crops (Brown et al., 1995; Mortensen and Strømme, 1987; Wollaeger and Runkle, 2014, 2015), which can explain the observation in the present study. For example, height of impatiens ‘Super Elfin XP Red’, salvia ‘Vista Red’ (*Salvia splendens*), and tomato ‘Early Girl’ seedlings was 37%–48%, 29%–50%, and 23%–49% shorter, respectively, under SSL LED treatments providing ≥10 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of B radiation than plants grown under LEDs providing 160 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of R radiation (Wollaeger and Runkle, 2015). More recently, transplants of cucumber ‘Elsie’ (*Cucumis sativus*) and pepper ‘Kathia’ were more compact under $B_{25}R_{95}$ LED SL and tomato ‘Climstar’ was more compact under $B_{25}R_{95}$ and HPS SL providing 25 $\mu mol \cdot m^{-2} \cdot s^{-1}$ compared to $B_{30}G_{30}R_{60}$, $B_{20}G_{10}R_{75}FR_{15}$, or HPS SL providing a *TPFD* of 120 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Garcia and Lopez, 2020). In general, seedlings were more compact when grown under a 9-h SD, HPS SL, or $B_{20}R_{50}$ LED SL for 28 to 35 d compared to seedlings grown under LED SL providing FR radiation (Fig. 2I-L).

Except for petunia (Rep. 1), similar trends in stem caliper were observed among genera and replications. For example, stem caliper of calibrachoa and petunia was greatest among all SL treatments compared to the 9-h SD; whereas stem caliper of impatiens and snapdragon was greater under HPS lamp SL compared to 9-h SD or $B_{15}R_{40}FR_{15}$ (28 d) SL (Fig. 2E-H). Similarly, Randall and Lopez, (2015) reported that the stem caliper of vinca ‘Titan Dark Red’, impatiens ‘Super Elfin XP Blue Pearl’, geranium ‘Bullseye Red’, and French marigold ‘Durango Yellow’ (*Tagetes patula*), was greater under HPS SL (DLI of 10.5 $mol \cdot m^{-2} \cdot d^{-1}$) compared to ambient light (DLI of 6.5 mol·m^{-2}·d^{-1}). Increasing stem caliper with increasing DLIs has also been reported for numerous young plants including angelonia 'AngelMist White Cloud' (*Angelonia angustifolia*), argyranthemum 'Madeira Cherry Red' (*Argyranthemum frutescens*), diascia 'Wink Coral' (*Diascia barberae*), nemesia 'Aromatica Royal' (*Nemesia fruticans*), osteospermum 'Voltage Yellow' (*Osteospermum ecklonis*), and verbena 'Aztec Violet' (*Verbena ×hybrida)* (Currey et al., 2012), cucumber 'Elsie', and pepper 'Kathia' (Garcia and Lopez, 2020).

SDM, RDM, R:S, SQ, and QI have been well documented to increase as DLI increases for both young and finished plants (Currey et al., 2012, 2013; Dou et al., 2018; Fausey et al., 2005; Faust et al., 2005; Gislerød et al., 1989). In the present study, RDM, SDM, R:S, and QI generally increased under SL compared to a 9-h SD (Fig. 3). Similarly, Poel and Runkle (2017a) reported increases in RDM of LDP snapdragon 'Montego Yellow' and petunia 'Wave Misty Lilac' seedlings were greatest among SL treatments providing 90 μmol·m^{-2}·s^{-1} compared to 10 μmol·m^{-2}·s^{-1}, whereas, the RDM and SDM of geranium 'Ringo 2000 Deep Scarlet', a DNP, was not different among SL treatments. Furthermore, cyclamen 'Metis Purple Flame' (*Cyclamen persicum*) had greater RDM and SDM under a 16-h photoperiod providing a DLI of 9.8 mol·m^{-2}·d^{-1} with an ADT of 20 °C compared to shorter photoperiods or ADT of 16 °C (Oh et al., 2008). Additionally, the RDM of begonia 'Bada Bing Scarlet' (*Begonia ×semperflorens*), gerbera 'Jaguar Deep Orange' (*Gerbera jamesonii*), and petunia 'Ramblin Peach Glo' seedlings were similar among HPS and LED SL treatments providing a *TPFD* of either 70 or 90 μmol·m^{-2}·s^{-1} (Hurt et al., 2019). In a separate study, the R:S and QI increased for nine ornamental genera, while the SQ increased for argyranthemum 'Madeira Cherry Red', nemesia 'Aromatica Royal', and osteospermum 'Voltage Yellow' as DLI increased from 1.2 to 12.3 mol·m^{-2}·d^{-1} (Currey and Lopez, 2012). The trends in these previous studies are consistent with our findings; however, it does not explain the variation we see for the SQ and QI between varying light qualities and should be further researched.

In some cases, RDM, SDM, R:S, seedling compactness, and SQ were greater under HPS lamp SL than LED SL (Figs. 2 and 3) which can be explained by the plant temperature. The average plant temperature was up to 1.2 (Rep. 1), 0.8 (Rep. 2), and 0.7 °C (Rep. 3) greater under HPS SL than LED SL (Table 2). Although HPS fixtures have become more efficient with time, they dissipate heat toward the plane that is illuminated whereas LEDs dissipate energy away from this plane and can cause plant temperature to rise by 1.3 °C under a *TPFD* of 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Nelson and Bugbee, 2015). It is likely that the increase in plant temperature under HPS SL increased developmental rates (Faust and Heins, 1997).

Leaf expansion generally occurs with FR radiation (Park and Runkle, 2017). In the present study, inconsistent trends between Rep. 1, 2, and 3 for leaf area, LMA, and LAI occurred for petunia (Fig. 4A-C). During Rep. 1, leaf area and LAI increased as the duration of FR radiation increased; however, the LMA was greatest under HPS SL compared to LED SL with FR radiation. Park and Runkle (2017) found that a decrease in the R:FR ratio or PPE increased the leaf area of geranium 'Pinto Premium Orange Bicolor' and snapdragon 'Trailing Candy Showers Yellow' seedlings. Furthermore, a low R:FR ratio, generally decreased LMA (Demotes-Mainard et al., 2016) which has been reported for chrysanthemum 'Refour' (*Chrysanthemum* ×*morifolium*) and tomato 'Ida' (Mortensen and Strømme, 1987). Our results for Rep. 1 are consistent with these previous studies. However, when petunia was grown under SL for only 28 d total (Rep. 2 and 3), the leaf area and LAI were greatest under HPS SL but were not different from seedlings under LED SL providing 14 d of FR radiation (Fig. 4A and C). Additionally, the LMA was greatest under HPS, $B_{20}R_{50}$, and $B_{15}R_{40}FR_{15}$ SL for 28 d (Fig. 4B).

Hurt et al. (2019) also reported no differences in leaf area of impatiens ‘Accent Premium Salmon’ and petunia ‘Ramblin Peach Glo’ under HPS and B_{10}:G_5:R_{85} LED SL providing a *TPFD* of 70 μmol·m^{-2}·s^{-1}. However, under HPS lamps providing a *TPFD* of 90 μmol·m^{-2}·s^{-1} leaf area was greater than all other SL treatments. Leaf area of geranium ‘Pinto Premium Salmon’, pepper ‘Long Red Slim Cayenne’, petunia ‘Single Dreams White’, and tomato ‘Supersweet’ were also not influenced by the addition of 12 μmol·m^{-2}·s^{-1} of FR radiation provided by LEDs (Poel and Runkle, 2017b). The only consistent trend between replications was that seedlings under SL had greater leaf area, LMA, and LAI than those under a 9-h SD. This can be attributed to the difference in DLI, which has also been reported for French marigold ‘Durango Yellow’, impatiens ‘Super Elfin XP Blue Pearl’, petunia ‘Dreams Midnight’, and vinca ‘Titan Dark Red’ (Randall and Lopez, 2015).

Finishing

Except for impatiens and petunia (Rep. 2 and 3), as the duration of FR radiation increased, time to visible bud and open flower decreased (Fig. 5A-H). For example, snapdragon seedlings grown under $B_{15}R_{40}FR_{15}$ LED SL (28 d) had visible buds and open flowers 3 to 4 d and 6 to 8 d earlier, respectively than those under HPS or $B_{20}R_{50}$ SL for 28 d, respectively (Fig. 5D and H). Our results are consistent with other studies that have found delays in flowering of LDPs under FR-deficient environments whereas, DNPs were unaffected (Park and Runkle, 2017; Poel and Runkle, 2017b; Runkle and Heins, 2001). For instance, when grown under $B_{12}G_{20}R_{68}FR_{12}$ LED SL snapdragon ‘Montego Yellow’ flowered 8 d earlier than LED SL without FR radiation (Poel and Runkle, 2017b). Additionally, subsequent time to flower of snapdragon ‘Trailing Candy Showers Yellow’ seedlings was hastened by 10 to 12 d with the addition or substitution of 16 to 64 μmol·m^{-2}·s^{-1} of FR radiation under LED SSL. However, flowering time, number of visible buds or flowers of geranium ‘Pinto Premium Orange Bicolor’, impatiens ‘Super Elfin XP Red’, or flowering time of petunia ‘Wave Blue’ were not influenced by LED SSL with or without FR radiation (Park and Runkle, 2017). Petunia ‘Wave Blue’ had 1.3 to 10.7 fewer flower buds when grown under $B_{32}R_{64}FR_{64}$ SSL providing an R:FR and PPE of 1:1 and 0.69, respectively, compared to higher R:FR and PPE treatments (Park and Runkle, 2017). Additionally, flowering of coreopsis ‘Early Sunrise’ (*Coreopsis grandiflora*) was delayed by 12 d when grown under an FR-deficient environment (Runkle and Heins, 2001). Our results further highlight the importance of providing FR radiation to LDPs during the seed stage; however, hastening time to flower of petunia ‘Wave Carmine Velour’ with FR radiation may be an exception to this.

Since visible bud and flower number were recorded at first open flower, our results show that in most cases there were not as many visible buds or flowers in treatments with hastened flowering (Fig. 5). As time progressed, the number of visible flower buds and flowers increased and appeared similar or greater than plants that took longer to flower (A.E. Kohler, personal observation). Although the number of lateral flower buds for snapdragon was not different among treatments, those grown under $B_{15}R_{40}FR_{15}$ SL had more flowers at the end of the study (A.E. Kohler, personal observation). In contrast, all plants in the 9-h SD treatment had not developed open flowers by the end of the study and were developmentally delayed (A.E. Kohler, personal observation).

Despite excessive stem growth of seedlings under SL providing FR radiation, the reduction in time to flower resulted in more compact petunia (Rep. 1) and snapdragon plants at first open flower (Fig. 6C-D). Similarly, snapdragon ‘Trailing Candy Showers Yellow’ was 18% to 28% shorter at first open flower when grown under LED SSL providing 16 to 64 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of FR radiation (Park and Runkle, 2017).

Comparable to stem elongation, the GI of calibrachoa (Rep. 1) and GI and lateral branch number for snapdragon decreased as duration of FR radiation increased (Fig. 6E, H and L). Similar findings for campanula 'Blå' (*Campanula isophylla*) occurred where FR radiation inhibited lateral branching compared to R radiation (Moe et al., 1991). Mortensen and Strømme (1987) also reported a reduction in lateral branches for chrysanthemum 'Refour' and tomato 'Ida' under a low R:FR, which is consistent with our findings. Furthermore, impatiens time to flower, number of visible buds and flowers, stem length, GI, and number of lateral branches (Figs 5 and 6) were not influenced by the addition of FR radiation. Impatiens is classified as shade tolerant and a DNP, therefore, FR radiation has little to no impact on their development (Mortensen and Strømme, 1987). Park and Runkle (2017), also reported that impatiens 'Super Elfin XP Red' time to flower, stem length, and number of visible buds and inflorescences was not influenced by the addition or substitution of 16 to 64 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of FR radiation with B and R LED SSL.

The inconsistent results for petunia 'Wave Carmine Velour', which is classified as a shade-intolerant and facultative LDP, were surprising as we would have expected similar findings to calibrachoa and snapdragon. Snapdragon had the strongest response to the addition of FR radiation, making it an excellent model crop to use for further FR radiation experiments.

Conclusion

Despite the consensus that FR radiation leads to excessive stem elongation, our findings conclude that FR radiation can be applied for 7 to 35 d during the seedling stage with no detrimental effects on finishing plant quality of both LDPs and DNPs. Although seedlings were generally taller under a DLI of 13 $mol \cdot m^{-2} \cdot d^{-1}$ from $B_{15}R_{40}FR_{15}$ LED SL compared to HPS or

$B_{20}R_{50}$ LED SL, this effect was not as pronounced under a DLI of 8 mol·m^{-2}·d^{-1}. Additionally, the RDM and SDM of calibrachoa, impatiens, petunia, and snapdragon were of similar quantity between HPS and LED SL treatments, with higher RDM and SDM recorded under higher DLIs (13 mol·m^{-2}·d^{-1}). Flowering of calibrachoa, petunia, and snapdragon was hastened by 4 to 8 d when grown under $B_{15}R_{40}FR_{15}$ LED SL for at least 14 d compared to HPS SL for 28 to 35 d. Hastened time to flower was correlated to a more compact or similar quality, finished plant. Thus, providing LDPs with at least 15 μmol·m^{-2}·s^{-1} of FR radiation during the last 14 d of seedling production under DLIs of 8 to 10 mol·m^{-2}·d^{-1} can improve finished crop quality and hasten flowering.

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APPENDIX

Table III-1. The total photon flux density (*TPFD*; mean ± SD), red (R; 600–700 nm) to far-red (FR; 700–800 nm) radiation ratio and estimated phytochrome photoequilibria (PPE; P_{fr}/P_{r+fr}) calculated according to Sager et al. (1988) provided by supplemental lighting from high-pressure sodium (HPS) or light emitting diode (LED) fixtures and duration of time for all treatments for Reps. 1, 2, and 3. Photon flux density ($\mu mol \cdot m^{-2} \cdot s^{-1}$) for blue (B; 400–500 nm), R, and FR radiation presented as subscripts for LED treatments.

		Duration (days)		*TPFD* ($\mu mol \cdot m^{-2} \cdot s^{-1}$)				
Treatment	Supplemental Lighting	Rep. 1	Rep. 2 & 3	Rep. 1	Rep. 2	Rep. 3	R:FR	PPE
1	None[z]	35	28	–[y]	–	–	–	–
2	HPS	35	28	72.8 ± 3.8	71.5 ± 1.8	69.8 ± 5.0	5:1	0.85
3	$B_{20}R_{50}$	35	28	68.0 ± 4.6	70.9 ± 1.3	69.9 ± 3.3	30:1	0.87
4	$B_{15}R_{40}FR_{15}$	35	28	72.2 ± 5.0	70.7 ± 1.1	71.6 ± 5.3	3:1	0.80
5	LEDs $B_{20}R_{50}$	14	14	68.0 ± 4.6	70.9 ± 1.3	69.9 ± 3.3	–	–
	$B_{15}R_{40}FR_{15}$	21	14	72.2 ± 5.0	70.7 ± 1.1	71.6 ± 5.3	–	–
6	$B_{20}R_{50}$	21	21	68.0 ± 4.6	70.9 ± 1.3	69.9 ± 3.3	–	–
	$B_{15}R_{40}FR_{15}$	14	7	72.2 ± 5.0	70.7 ± 1.1	71.6 ± 5.3	–	–

[z]No supplemental lighting to report additional *PFD*.
[y]No data to report.

Table III-2. Mean ± SD air and plant temperature and daily light integral (DLI) during the seedling and finishing stage for each treatment.

		Temperature (°C)		DLI
Start date	Treatment	Air	Plant	($mol \cdot m^{-2} \cdot d^{-1}$)
		Seedling stage		
25 Feb. 2019	9-h short day	22.8 ± 2.3	24.4 ± 1.5	9.2 ± 4.4
	HPS	23.2 ± 2.4	23.2 ± 1.1	13.8 ± 4.1
	$B_{20}R_{50}$ LEDs	22.4 ± 1.6	23.0 ± 1.1	12.9 ± 4.2
	$B_{15}R_{40}FR_{15}$ LEDs	22.4 ± 2.0	22.0 ± 1.5	12.4 ± 3.7
18 Nov. 2019	9-h short day	22.7 ± 1.2	22.4 ± 1.4	3.5 ± 1.3
	HPS	22.9 ± 0.9	23.3 ± 2.1	7.1 ± 1.2
	$B_{20}R_{50}$ LEDs	22.8 ± 1.0	22.5 ± 1.4	7.0 ± 1.2
	$B_{15}R_{40}FR_{15}$ LEDs	22.7 ± 0.8	23.5 ± 1.3	6.1 ± 1.2
14 Jan. 2020	9-h short day	23.4 ± 1.0	23.6 ± 1.6	3.7 ± 1.8
	HPS	23.2 ± 1.6	22.4 ± 1.8	8.2 ± 1.6
	$B_{20}R_{50}$ LEDs	22.9 ± 1.0	21.9 ± 1.9	8.0 ± 1.6
	$B_{15}R_{40}FR_{15}$ LEDs	23.2 ± 1.3	21.7 ± 1.8	8.0 ± 1.9
		Finishing stage		
01 Apr. 2019		20.4 ± 1.6		19.4 ± 7.8
17 Dec. 2019		19.8 ± 0.7		9.5 ± 3.0
12 Feb. 2020		19.8 ± 0.9		14.5 ± 5.0

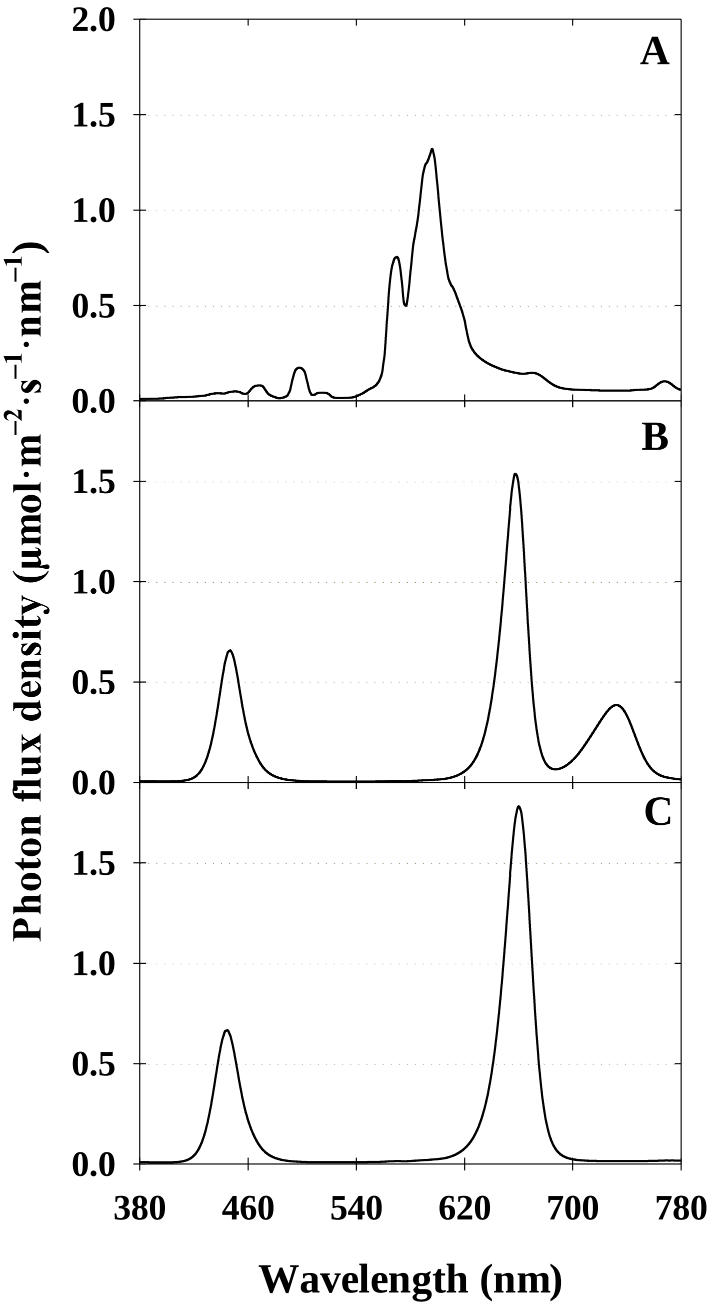

Figure III-1. Spectral quality delivered from high-pressure sodium lamps (A) and light-emitting diode (LED) fixtures providing a photon flux density (*PFD*) in µmol·m^{-2}·s^{-1} of blue (B, 400–500 nm), red (R, 600–700 nm), and far-red (FR, 700–800 nm) radiation of $B_{15}R_{40}FR_{15}$ (B) and $B_{20}R_{50}$ radiation (C).

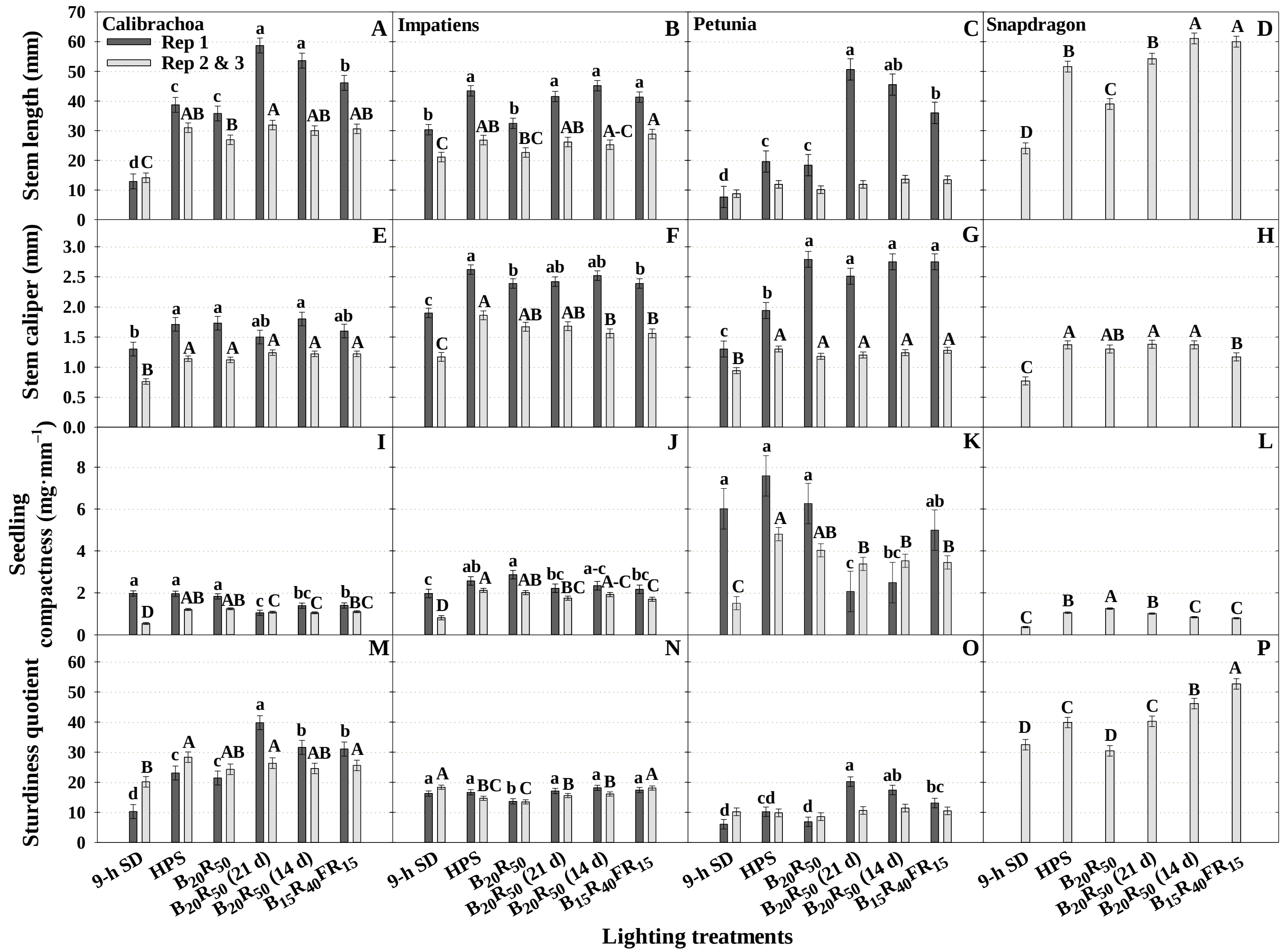

Figure III-2. Stem length and caliper, seedling compactness, and sturdiness quotient for calibrachoa, impatiens, petunia, and snapdragon seedlings 35 (Rep. 1) or 28 d (Rep. 2 and 3) under lighting treatments of 9-h short day (SD), high-pressure sodium (HPS) supplemental lighting (SL), or light emitting diode (LED) SL providing photon flux densities ($\mu mol \cdot m^{-2} \cdot s^{-1}$) as subscripts of blue (B, 400–500 nm), red (R; 600–700 nm), and far-red (FR; 700–800 nm) radiation as $B_{20}R_{50}$, $B_{20}R_{50}$ (21 d) + $B_{15}R_{40}FR_{15}$ (14 or 7 d), $B_{20}R_{50}$ (14 d) + $B_{15}R_{40}FR_{15}$ (21 or 14 d), and $B_{15}R_{40}FR_{15}$ LED SL. Bars and error bars represent mean and SEs, respectively. Different letters within replications are significantly different between treatments using Fisher's least significant difference (LSD) test at $P \leq 0.05$.

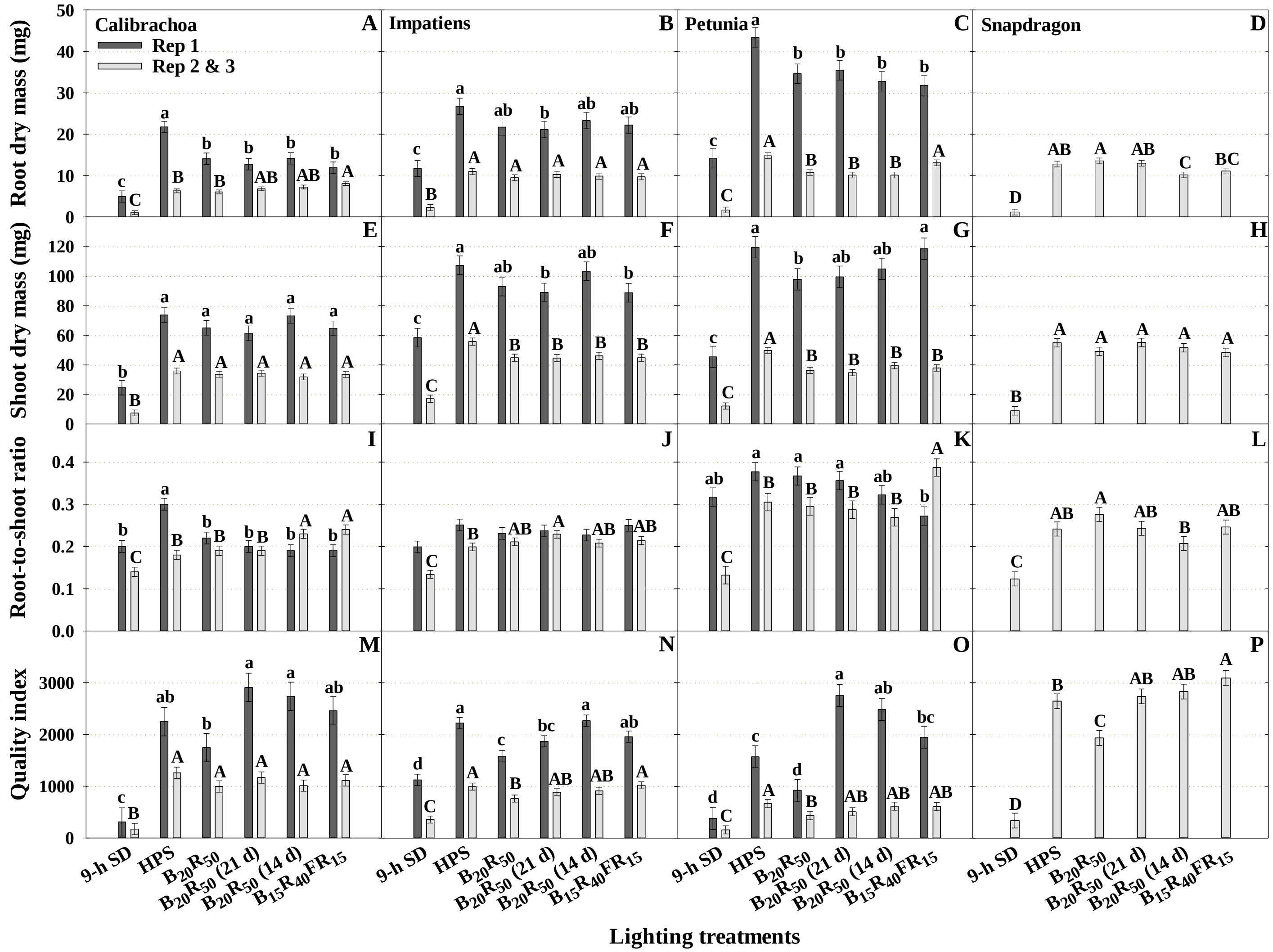

Figure III-3. The root dry mass, shoot dry mass, root-to-shoot dry mass ratio, and quality index [total dry mass × (root-to-shoot ratio + sturdiness quotient)] of calibrachoa, impatiens, petunia, and snapdragon seedlings 35 (Rep. 1) or 28 d (Rep. 2 and 3) under lighting treatments. Bars and error bars represent mean and SEs, respectively. Different letters within replications are significantly different between treatments using Fisher's LSD test at $P \leq 0.05$.

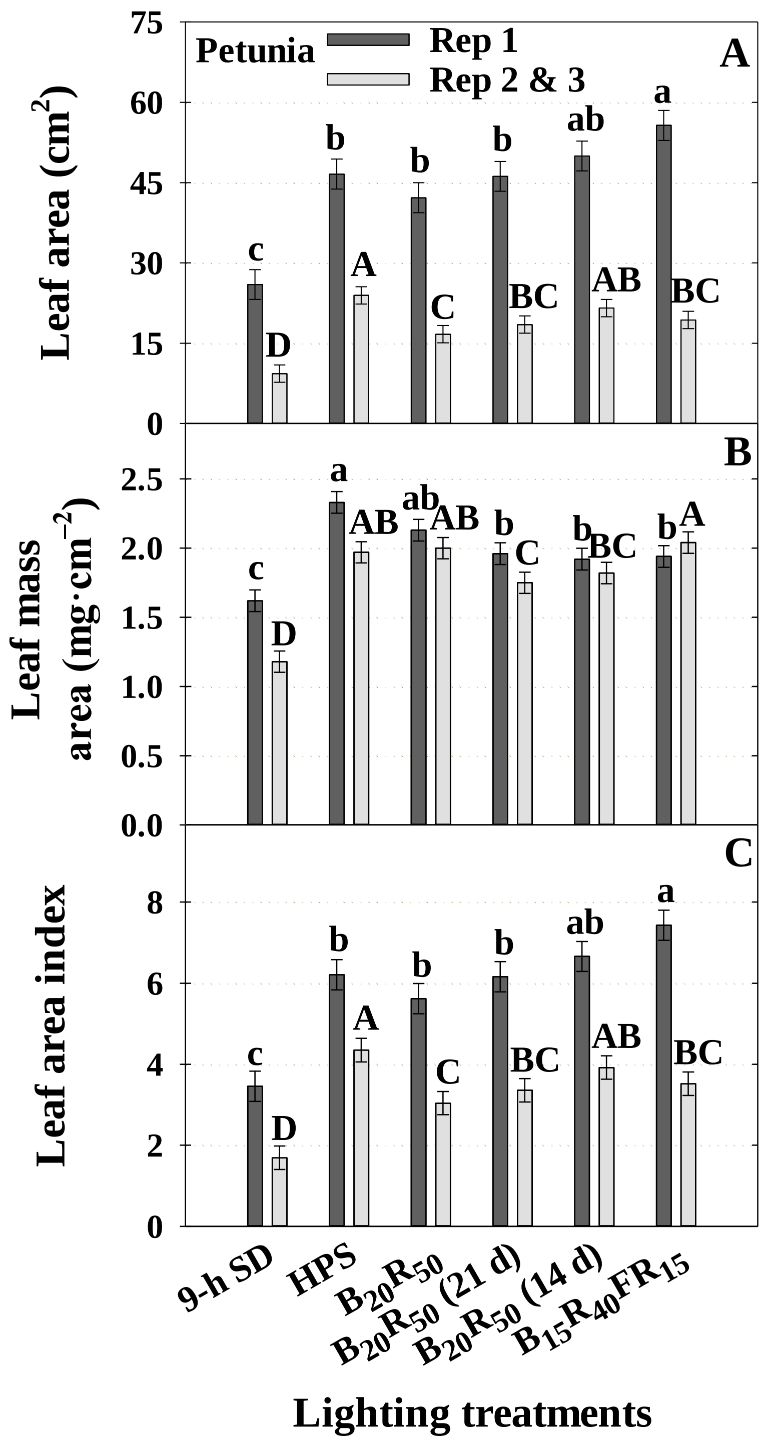

Figure III-4. The leaf area, leaf mass area, and leaf area index of petunia seedlings 35 (Rep. 1) or 28 d (Rep. 2 and 3) under lighting treatments. Bars and error bars represent mean and SEs, respectively. Different letters within replications are significantly different between treatments using Fisher's LSD test at $P \leq 0.05$.

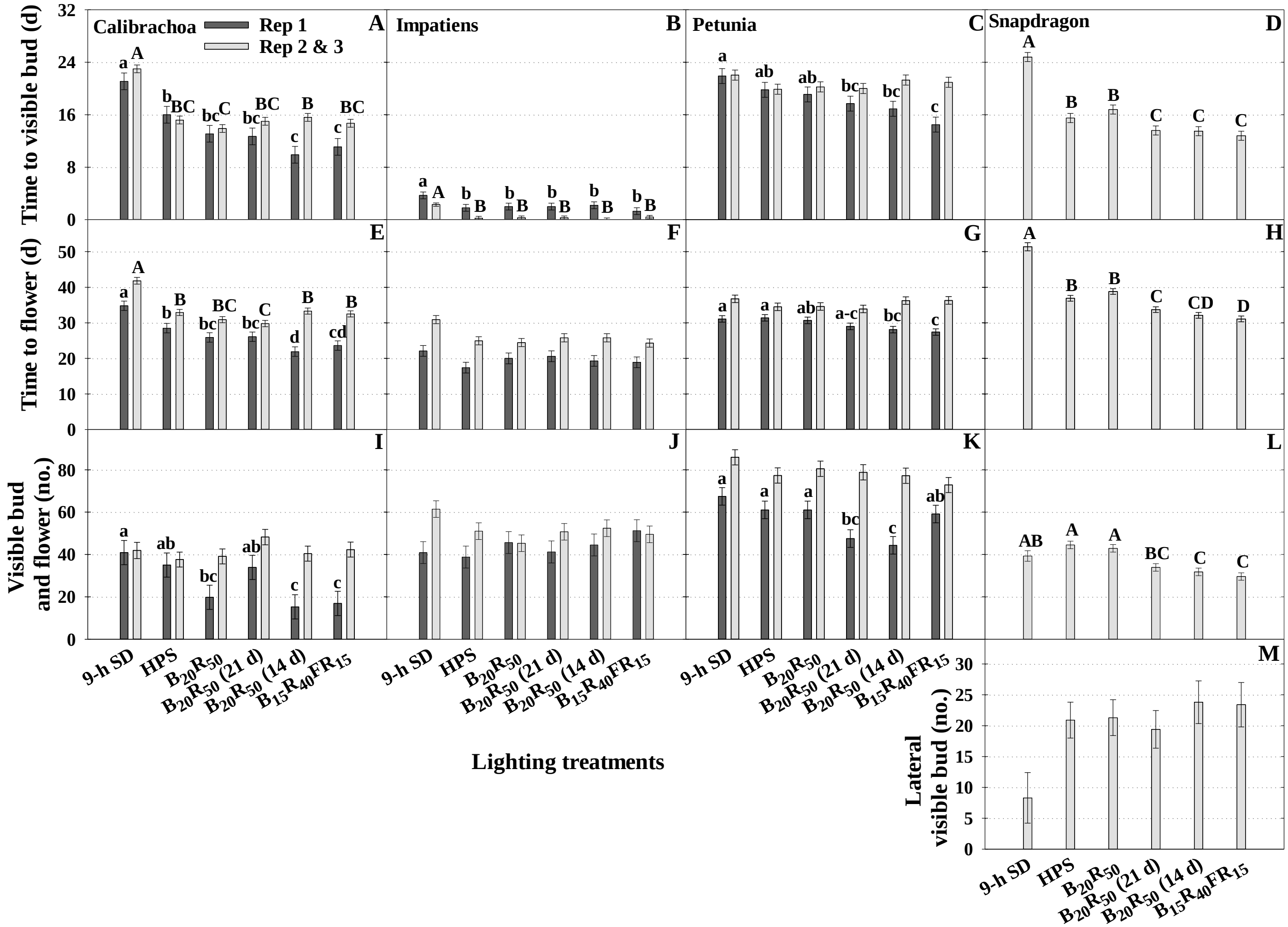

Figure III-5. Time to visible flower bud and first open flower, number of visible flower buds and flowers, and number of lateral visible flower buds (snapdragon) for calibrachoa, impatiens, petunia, and snapdragon that were previously grown under lighting treatments for 35 (Rep. 1) or 28 d (Rep. 2 and 3). Bars and error bars represent mean and SEs, respectively. Different letters within replications are significantly different between treatments using Fisher's LSD test at $P \leq 0.05$.

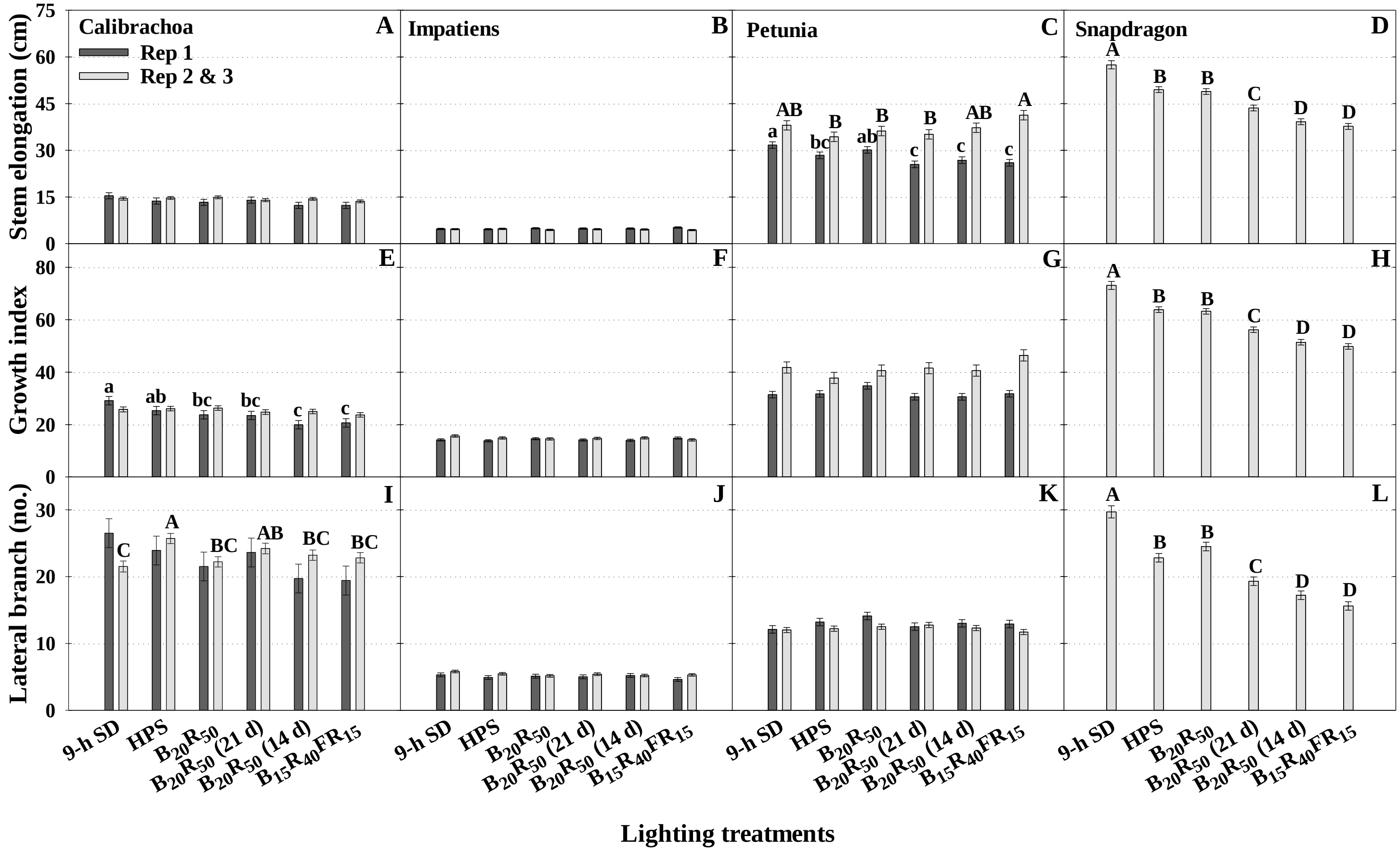

Figure III-6. The stem elongation (stem length of calibrachoa, impatiens, and snapdragon and longest shoot of petunia), growth index, and number of lateral branches for calibrachoa, impatiens, petunia, and snapdragon previously grown under lighting treatments for 35 (Rep. 1) or 28 d (Rep. 2 and 3). Bars and error bars represent mean and SEs, respectively. Different letters within replications are significantly different between treatments using Fisher's LSD test at $P \leq 0.05$.

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SECTION IV

DAILY LIGHT INTEGRAL INFLUENCES ROOTING OF HERBACEOUS STEM-TIP CULINARY HERB CUTTINGS

Daily light integral influences rooting of herbaceous stem-tip culinary herb cuttings

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Abstract

Domestic production of culinary herbs has been increasing in the United States but have yet to meet the increasing demands. Culinary herbs can be grown from seeds, however some crops grown from seed grow slowly or result in poor germination. Thus there are advantages of propagating by vegetative cuttings which produce fast, true-to-type plants. Previous research of ornamental young plants and finished culinary herbs have shown increases in plant quality with increases in the daily light integral (DLI). To our knowledge, little to no research has addressed how the DLI influences culinary herb liner quality. Thus, to improve production efficiencies, the objectives of this study were to quantify morphological traits of five economically important culinary herbs when grown under DLIs ranging from 2.8 to 16.4 mol·m^{-2}·d^{-1}. Stem-tip cuttings of oregano (*Origanum vulgare*), rosemary 'Arp' (*Rosmarinus officinalis*), sage 'Extrakta' (*Salvia officinalis*), spearmint 'Spanish' (*Mentha spicata*), and thyme 'German Winter' (*Thymus vulgaris*) were excised from stock plants and placed on a bench in a glass-glazed greenhouse compartment with a 56% aluminum shade cover to provide a callusing DLI of ≈5 mol·m^{-2}·d^{-1} with air and root-zone temperatures of 24 °C and a vapor pressure deficit of 0.3 kPa. After 5 d, one tray per genera was moved to a bench that provided no shade or aluminum shading of 36%, 56%, or 76% to create a range of DLI treatments. After 9 d (spearmint) or 16 d (all other genera) of DLI treatments, the root, shoot, and total dry mass of all culinary herb liners generally increased by 105%–449%, 52%–142%, and 82%–170%, respectively, as DLI increased. Stem length of oregano, spearmint, and thyme decreased by 37%, 28%, and 27%, respectively, as DLI increased from 2.8 to 16.4 mol·m^{-2}·d^{-1}. However, stem length of rosemary and sage were not affected by DLI. The quality index of all genera was greatest at a DLI optimums from 10.4 to 16.4 mol·m^{-2}·d^{-1}. Furthermore, all culinary herbs grown under a DLI of ≤6 mol·m^{-2}·d^{-1} had low

root and shoot dry mass accumulation and oregano, spearmint, and thyme were generally taller. Therefore, vegetative propagation of culinary herbs should be conducted at a DLI between 10 to 12 $mol \cdot m^{-2} \cdot d^{-1}$ and DLIs of $\geq$15 $mol \cdot m^{-2} \cdot d^{-1}$ may be deleterious and energy inefficient.

Keywords: *Mentha spicata*, *Origanum vulgare*, propagation, *Rosmarinus officinalis*, *Salvia officinalis*, *Thymus vulgaris*, young plants

Abbreviations: ADT, average daily temperature; DLI, daily light integral; HPS, high-pressure sodium; *PPFD*, photosynthetic photon flux density; QI, quality index; RDM, root dry mass; R:S, root-to-shoot ratio; SDM, shoot dry mass; SQ, sturdiness quotient; TDM, total dry mass; VPD, vapor-pressure deficit

Introduction

The market demand for fresh, dried, and living culinary herbs has increased over the past decade. In 2014, the wholesale value of culinary herbs produced in the United States (U.S.) was U.S. $96.8 million, a 64% increase from 2009 (USDA, 2010, 2015). Furthermore, culinary herbs produced under protected environments has increased 2.3-fold from 2009 to 2014 with 1.3 million m^2 of production valued at $70.9 million in 2014 (USDA, 2010, 2015). However, U.S. herb imports have increased from $360 million in 2014 to $414 million in 2018 (UN COMTRADE, 2020).

The recent increase in domestic production is from protected cultivation such as row covers, high tunnels, and greenhouses, which has allowed for off-season production of culinary herbs creating year-round local availability, with the potential to increase profits (Anon., 2006).

Culinary herb production generally begins in greenhouses via seed sowing or transplanting vegetative cuttings. The latter is used when seeds are difficult to produce, have poor or slow germination, or when a true-to-type plant is required (Dole and Hamrick, 2006). Additionally, greenhouses allow for control of environmental conditions such as temperature and radiation intensity, which are critical to producing high-quality plugs and liners. Of the environmental conditions, radiation intensity has been documented as directly influencing propagation time and liner quality.

The total number of photons available over a 24-h period is known as the photosynthetic daily light integral (DLI). The DLI recommendations of crops can be <5, 5 to 10, 10 to 20, and >20 $mol \cdot m^{-2} \cdot d^{-1}$ and thus can be classified as very low, low, medium, and high, respectively (Faust, 2011). During peak propagation in Northern latitudes, DLIs can be as low as 2 $mol \cdot m^{-2} \cdot d^{-1}$ inside a greenhouse due to seasonal short days, low ambient light, and even greenhouse glazing and infrastructure (Faust, 2011). To increase greenhouse DLI, supplemental lighting from high-pressure sodium (HPS) lamps or light-emitting diodes are often used. A minimum DLI of ≈5 $mol \cdot m^{-2} \cdot d^{-1}$ inside the greenhouse is recommended for propagation of herbaceous ornamental crops, with an increase in DLI to ≥8 $mol \cdot m^{-2} \cdot d^{-1}$ for further biomass accumulation (Lopez and Runkle, 2008).

In general, increasing the DLI increases biomass accumulation and decreases stem elongation until plants become light saturated (Faust et al., 2005; Currey et al., 2012). For example, shoot dry mass (SDM) and root dry mass (RDM) of petunia ‘Tiny Tunia Violet Ice’, ‘Double Wave Spreading Rose’, and ‘Supertunia Mini Purple’ (*Petunia ×hybrida*) after 16 d of propagation increased 506% and 680%, 106% and 2,395%, 147% and 108% as DLI increased from 1.2 to 8.4 $mol \cdot m^{-2} \cdot d^{-1}$, respectively (Lopez and Runkle, 2008). Height of cuttings decreased by 29%, 25%, and 36% as DLI increased from 1.2 to 5.9 mol·m^{-2}·d^{-1} for liners of petunia 'Tiny Tunia Violet Ice', 'Double Wave Spreading Rose' and 'Supertunia Mini Purple', respectively (Lopez and Runkle, 2008). Additionally, Currey et al. (2012) reported stem length, stem caliper, and total dry mass (TDM) of diascia 'Wink Coral' (*Diascia barberae*) to increase by 76%, 160%, and 465%, respectively, as DLI increased from 1.2 to 12.3 mol·m^{-2}·d^{-1} (Currey et al., 2012). In contrast, DLI did not affect stem length during propagation of New Guinea impatiens 'Celebration Pink' (*Impatiens hawkeri*), geranium 'Fantasia Dark Red' (*Pelargonium ×hortorum*), and petunia 'Suncatcher Midnight Blue' (Currey and Lopez, 2015). Furthermore, as DLI increased from 2.0 to 13.4 mol·m^{-2}·d^{-1} root, stem, and leaf dry mass of New Guinea impatiens 'Celebration Pink' increased by 211%, 104%, and 99% respectively, after 14 d of DLI treatments (Currey and Lopez, 2015).

In addition to influencing growth and development of ornamental young plants, DLI similarly influences growth of culinary herbs. Litvin-Zabal (2019) reported shoot fresh and dry mass increased with increasing DLI for hydroponically grown mint (*Mentha* spp.), oregano (*Origanum vulgare*), sage (*Salvia officinalis*), and thyme (*Thymus vulgaris*). As DLI increased from 2 to 20 mol·m^{-2}·d^{-1}, shoot fresh mass of mint and sage increased curvilinearly to 52.6 and 43.0 g at DLIs of 14.9 and 15.9 mol·m^{-2}·d^{-1}, respectively (Litvin-Zabal, 2019). The SDM of mint, thyme, and oregano increased linearly by 16.4, 3.2, and 1.2 g, respectively, as DLI increased to 20 mol·m^{-2}·d^{-1} (Litvin-Zabal, 2019). Sweet basil 'Improved Genovese Compact' (*Ocimum basilicum*), RDM was greater at a DLI of 16.5 mol·m^{-2}·d^{-1} compared to DLIs of 9.3, 11.5, 12.9, and 17.8 mol·m^{-2}·d^{-1} after 21 d of treatments (Dou et al., 2018). Additionally, Mapes and Xu (2014) reported the height of sage grown for 84 d to be 0.67, 0.87, and 1.35-times taller under DLIs of 6.5, 4.5, and 3.1 mol·m^{-2}·d^{-1}, respectively, compared to a DLI of 9.2 mol·m^{-2}·d^{-1}.

The fresh shoot mass of sage stems and leaves was 155% to 215% greater when grown at a DLI of 9.2 $mol·m^{-2}·d^{-1}$ compared to lower DLI treatments (Mapes and Xu, 2014). Fausey et al. (2005) also reported SDM increased as DLI increased from 5 to 20 $mol·m^{-2}·d^{-1}$ for lavender 'Hidcote Blue' (*Lavandula angustifolia*). Overall plant quality also improved from weak stems, lateral branching, and green foliage to upright stems, extensive branching, and gray foliage as DLI increased to 20 $mol·m^{-2}·d^{-1}$, concluding that a DLI of at least 15 to 20 $mol·m^{-2}·d^{-1}$ should be provided for finished lavender production (Fausey et al., 2005).

From a U.S. hydroponic grower survey conducted in 2017, 43% of respondents indicated that research focused on DLI would be very beneficial (Walters et al., 2020). However, 54% indicated they used supplemental lighting during propagation compared to 45% during finished production. Of those respondents, only 45% and 32% monitored the DLI or instantaneous radiation intensity, respectively (Walters et al., 2020). It is apparent from previous research that increasing DLI during propagation of ornamental crops and finished culinary herbs reduces production time and increases quality and yield. One of the only studies conducted on radiation quantity during seed propagation of thyme and sweet basil showed an increase in average fresh mass accumulation, but specific DLIs were not reported (Raviv and Putievsky, 1988). Thus to our knowledge little to no research has highlighted the impact DLI has on the propagation of culinary herbs by shoot-tip cuttings.

Therefore, the objective of our study was to quantify the morphological and physiological effects of DLI on the vegetative propagation of five commercially important culinary herbs. We hypothesized that propagation DLIs $\geq$10 $mol·m^{-2}·d^{-1}$ will provide the highest quality liner with greater RDM, stem caliper, and shorter stem lengths compared to DLIs of $\leq$5 $mol·m^{-2}·d^{-1}$.

Materials and methods

Stock plants and environment

Stock plants of oregano, sage ‘Extrakta’, spearmint ‘Spanish’ (*Mentha spicata*), thyme ‘German Winter’ (Johnny’s Selected Seeds, Fairfield, ME), and rosemary ‘Arp’ (*Rosmarinus officinalis*) (Dümmen Orange NA, Inc., Columbus, OH) were grown in 15.3 cm (1.3-L; The HC Companies, Twinsburg, OH) round containers filled with a 70% peat, 21% perlite, and 9% vermiculite substrate mixture (Suremix; Michigan Grower Products, Inc., Galesburg, MI). Plants were irrigated as necessary with reverse osmosis water and a water-soluble fertilizer (Orchid RO Water Special 13N–1.8P–12.5K; Greencare Fertilizers, Inc., Kankakee, IL) providing ($mg \cdot L^{-1}$): 125 N, 12 P, 120 K, 78 Ca, 19 Mg, 0.2 B, 0.4 Cu, 1.7 Fe, 0.9 Mn, 0.2 Mo, and 0.4 Zn.

Oregano, spearmint, rosemary, and thyme were grown in a glass-glazed greenhouse in the Plant Science Research Greenhouse ranges at Michigan State University [(MSU), East Lansing, MI (lat. 43° N)] with an air average daily temperature (ADT) of 21 ± 4 °C and a mean DLI of 12.1 $mol \cdot m^{-2} \cdot d^{-1}$. The mean DLI one month before cutting harvest was 11.6, 10.1, and 9.7 $mol \cdot m^{-2} \cdot d^{-1}$ for replications 1, 2, and 3, respectively. Since oregano, spearmint, and thyme are long-day plants and rosemary (photoperiodic response unknown), they were grown under a 9-h photoperiod to maintain vegetative growth. The photoperiod consisted of a truncated 9-h natural day achieved by using blackout cloth from 1700 to 0800 HR. From 0800 to 1700 HR, HPS lamps (LR48877; P.L. Light Systems; Beamsville, ON, Canada) provided a supplemental photosynthetic photon flux density (*PPFD*) of 70 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at plant height [as measured with a quantum sensor (LI-190R; LI-COR Biosciences, Lincoln, NE)] when the ambient greenhouse *PPFD* was <400 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Sage stock plants, which are presumed to be short-day plants, were maintained under a 16-h photoperiod at an ADT of 22 ± 3 °C and a mean DLI of 17.5

mol·m^{-2}·d^{-1}. The mean DLI one month before cuttings were harvested, were 11.3, 13.7, and 10.3 mol·m^{-2}·d^{-1} for replications 1, 2, and 3, respectively. The photoperiod consisted of natural daylengths with day-extension lighting from HPS lamps that delivered a supplemental *PPFD* of 70 µmol·m^{-2}·s^{-1} at plant height. All stock plants were periodically cut back as necessary to increase branching and number of harvestable cuttings.

Plant material and callusing environment

One hundred fifty, 3 to 4 cm vegetative stem-tip cuttings were excised from stock plants of oregano, rosemary, sage, spearmint, and thyme on 09 Sept. 2019, 03 Oct. 2019, and 07 Jan. 2020. Cuttings of each genera were inserted immediately, without rooting hormone, into two 72-cell trays (28-mL individual cell volume; Landmark Plastics, Akron, OH) that were divided in half and filled with a propagation mix made from 50% of soilless substrate mentioned above (Suremix; Michigan Grower Products Inc.) and 50% coarse perlite.

All four trays per genera were placed in one of two glass-glazed greenhouse compartments with an air ADT set point of 24 °C and vapor pressure deficit (VPD) of 0.3 kPa on propagation benches with a root-zone heating (Biotherm® Benchwarmer Kit; TrueLeaf Technologies, Petaluma, CA) set point of 24 °C for 5 d to callus. A Priva Environmental Monitoring Box (Integro 725-3030; Priva North America, Vineland Station, ON, Canada) positioned in the middle of each greenhouse compartment housed a thermocouple to measure air temperature and a thermocouple inserted into a moist wick to measure the VPD. The root-zone heating temperature was measured with two thermistors and a thermocouple which were placed into three cells along the long edge of a propagation tray, 2.6 cm in depth, filled with propagation substrate as mentioned above. The callusing bench was covered with a 56% aluminum shade cloth (Solaro 5220 D O; Ludvig Svensson Inc, Charlotte, NC) and under a 16-h photoperiod

(0600 to 2200 HR) provided by natural daylight and supplemental lighting from HPS lamps when outdoor light intensity was below ≈400 μmol·m^{-2}·s^{-1} to achieve a DLI of ≈5 mol·m^{-2}·d^{-1}, which was measured every 10 s by a quantum sensor (LI-190R; LI-COR Biosciences) positioned in the middle of the bench. An infrared sensor (Type T, OS36-01; Omega Engineering, Stamford, CT) was pointed approximately 2.0 cm above spearmint leaves to measure plant temperature. Averages of air, plant, and root-zone temperature, DLI, and VPD for all replications are shown in Table 1.

Overhead mist (0500 to 2300 HR) containing reverse-osmosis water supplemented with water-soluble fertilizer (MSU Plug Special 13N–2.2P–10.8K; Greencare Fertilizers, Inc.) and a micronutrient supplement (M.O.S.T.; JR Peters, Inc., Allentown, PA) was provided as necessary and delivered the following (mg·L^{-1}): 60 N, 10 P, 50 K, 28 Ca, 5 Mg, 27 S, 16 Fe, 10 Zn, 17 Mn, 5 Cu, 3 B, and 0.2 Mo. The mist was regulated by an environmental computer that accounted for the function of time and accumulated *PPFD*. A line quantum sensor (Apogee Instruments, Inc., Logan, UT) positioned in the center of the propagation house recorded light intensity every 10 s. When the integrated light intensity achieved 0.20 mol·m^{-2}·h^{-1} or after 60 min, whichever first occurred, the mist would turn on for 5 s. A VPD of 0.3 kPa was maintained by the injection of steam.

Daily light integral treatments

After callusing, one tray of each species was distributed among four different DLI treatments that were created by aluminum shade cloth providing shading percentages per the manufacturer of 76% (Solaro 7330 O FB; Ludvig Svensson Inc.), 56%, or 36% (Solaro 3215 D O FB; Ludvig Svensson Inc.) shading or no shade to achieve a range of DLIs over time (Table 1). Each DLI treatment was randomized between the two propagation houses and three benches in each house.

Quantum sensors were positioned in the middle of each bench to record the light quantity and air, plant, and root-zone temperature were measured as stated above. All measurements were recorded every 10 s and averages accumulated every hour using a data logger (CR-1000; Campbell Scientific, Logan, UT). Mist was reduced every 4 d during the experiment and discontinued 7 d before data collection. Liners were irrigated with the same water-soluble fertilizer (MSU Plug Special 13N–2.2P–10.8K; Greencare Fertilizers, Inc.) and a micronutrient supplement (M.O.S.T.; JR Peters, Inc.).

Data collection

Ten cuttings per DLI treatment were harvested 9 d (spearmint) or 16 d (all other genera) after callusing. Spearmint was harvested on 23 Sept. 2019, 17 Oct. 2019, and 21 Jan. 2020 while all other genera were collected on 30 Sept. 2019, 24 Oct. 2019, and 28 Jan. 2020. Before measurements, each cutting was assessed for pullability and the substrate was gently washed from the roots and shoots. Pullability was assessed by the ability to pull the liner from the cell while keeping at least 95% of the substrate intact. On each harvest date, stem length was measured with a ruler from the base of the stem to the apical meristem and stem caliper was measured by a digital caliper below the first true leaves. Each cutting was divided into roots and shoots, placed in a drying oven at 70 °C for 3 d and then weighed for RDM and SDM, respectively. Measurements of stem length, stem caliper, RDM, and SDM were used to determine the root-to-shoot ratio (R:S; R:S = RDM/SDM), total dry mass (TDM = RDM + SDM), sturdiness quotient (SQ; SQ = stem length/stem caliper), and the quality index [QI; QI = TDM × (R:S + SQ)] (Currey et al., 2013).

Experimental design and statistical analysis

The experiment was designed as a randomized complete block with DLI as a random factor. The experimental units were the individual cuttings, which were randomly assigned to each DLI treatment. The experiment was performed three times across benches and propagation houses with 10 samples per DLI treatment. Data were analyzed using the generalized linear mixed model procedure (PROC GLIMMIX) and linear and quadratic regression (PROC REG) in SAS (version 9.2; SAS Institute, Cary, NC) with means separated by Fisher's least significant difference (LSD) test at $P \leq 0.05$. When linear and quadratic regression formulas were both significant, the line with the higher value of fit (r^2 or R^2) was the deciding factor.

Results

For all crops, the RDM, SDM, and TDM increased as the DLI increased to crop-specific optimums. As DLI increased from 2.8 to 16.4 mol·m^{-2}·d^{-1}, the RDM of sage increased linearly by 421% (Fig. 1B). The optimal DLI for oregano and thyme were at 12.1 and 13.9 mol·m^{-2}·d^{-1}, respectively, where the RDM were 106% and 436% greater, respectively, than a DLI of 2.8 mol·m^{-2}·d^{-1} (Fig. 1A). Further increases in DLI for these genera did not result in an increase in RDM. The RDM of rosemary and spearmint increased curvilinearly as DLI increased from 2.8 to 16.4 mol·m^{-2}·d^{-1} but the optimal DLIs were outside of the range studied (Fig. 1A-B). The SDM of oregano and spearmint increased linearly to 169 and 189 mg, respectively, as DLI increased from 2.8 to 16.4 mol·m^{-2}·d^{-1}. Whereas the SDM of rosemary, sage, and thyme increased curvilinearly with optimal DLIs occurring at 14.5 (138 mg), 12.5 (290 mg), and 13.2 (55 mg) mol·m^{-2}·d^{-1}, respectively (Fig. 1C-D). Additionally, the TDM of oregano and spearmint increased linearly from 93 to 207 mg and 105 to 260 mg, respectively, as DLI increased from 2.8

to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$, respectively (Fig. 1E). The TDM of rosemary, sage, and thyme increased curvilinearly by 103%, 125%, and 216%, respectively, at optimal DLIs of 16.3, 13.5, and 13.4 $mol \cdot m^{-2} \cdot d^{-1}$, respectively (Fig. 1E-F).

A high R:S is desirable for young plant production. For all crops, the R:S increased for all to crop-specific DLIs (Fig. 1G-H). The R:S of sage increased linearly as DLI increased from 2.8 to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ from 0.08 to 0.25 (Fig 1H). The R:S increased curvilinearly for oregano, rosemary, spearmint, and thyme as DLI increased from 2.8 to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ (Fig. 1G-H). For instance, the R:S of oregano increased from 0.21 to 0.27 as DLI increased from 2.8 to 9.6 $mol \cdot m^{-2} \cdot d^{-1}$, respectively, then decreased to 0.21 at a DLI of 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ (Fig. 1G). The R:S of rosemary increased curvilinearly from 0.09 to 0.28 as DLI increased from 2.8 to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$, respectively, but the optimal DLI was calculated outside of the studied range (Fig. 1H). Additionally, as DLI increased from 2.8 to 12.1 $mol \cdot m^{-2} \cdot d^{-1}$, the R:S for spearmint increased from 0.17 to 0.38, respectively, and decreased to 0.33 at a DLI of 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ (Fig. 1G). From a DLI of 2.8 to 12.6 $mol \cdot m^{-2} \cdot d^{-1}$, the R:S of thyme increased from 0.10 to 0.27, respectively, and decreased to 0.24 at a DLI of 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ (Fig. 1G).

The DLI only influenced the stem length for oregano, spearmint, and thyme, and had no influence for rosemary or sage (Fig. 2A-B). The stem length of spearmint decreased curvilinearly by 12% as DLI increased from 2.8 to 12.7 $mol \cdot m^{-2} \cdot d^{-1}$, then slightly increased as the DLI increased to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ (Fig. 2A). Stem length of oregano and thyme decreased linearly by 36% and 27%, respectively as DLI increased from 2.8 to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ (Fig. 2A). As the DLI increased, the stem caliper for all crops increased variably (Fig. 2C-D). The stem caliper of sage and thyme increased curvilinearly by 23% and 49%, respectively, from a DLI of 2.8 $mol \cdot m^{-2} \cdot d^{-1}$ to DLI optimums of 10.8 and 14.8 $mol \cdot m^{-2} \cdot d^{-1}$, respectively (Fig. 2C-D). Stem caliper of oregano, rosemary, and spearmint increased linearly as DLI increased from 2.8 to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ by 26%, 28%, and 30%, respectively (Fig. 2C–D).

The SQ decreased curvilinearly for sage and spearmint as DLI increased to optimums of 11.1 and 13.3 $mol \cdot m^{-2} \cdot d^{-1}$, respectively (Fig. 2E-F). For spearmint, the SQ decreased by 27% as DLI increased from 2.8 to 13.3 $mol \cdot m^{-2} \cdot d^{-1}$, respectively, then increased as the DLI increased to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ (Fig. 2E). As DLI increased, the SQ of oregano, rosemary, and thyme decreased linearly (Fig. 2E-F). For example, as DLI increased from 2.8 to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$, the SQ of thyme decreased by 53% (Fig. 2E). The QI of oregano, rosemary, and thyme increased curvilinearly to optimal DLIs of 10.9, 15.1, and 10.4 $mol \cdot m^{-2} \cdot d^{-1}$, respectively, yielding a QI of 631, 501, and 1,070, respectively (Fig. 2G–H). As DLI increased from 2.8 to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$, the QI of spearmint increased by 53% (Fig. 2G). Additionally, the QI of sage increased linearly by 93% as the DLI increased from 2.8 to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ (Fig. 2H).

Discussion

High-quality plugs and liners have a high RDM, are compact, and have thick stems to allow for ease of transportation and transplanting (Currey et al., 2012; Pramuk and Runkle, 2005). Plant characteristics such as RDM, SDM, leaf area, stem and stem caliper give insight to overall plant quality and are greatly influenced by radiation intensity (Currey et al., 2012; Faust et al., 2005; Pramuk and Runkle, 2005). From this experiment, the RDM, SDM, and stem caliper of all culinary herbs increased and stem length decreased or had no change to a genera-specific DLI maxima as DLI increased from 2.8 to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ (Fig. 1A-D and 2A-D). These data are similar to previous findings in young ornamental plant production. For example, as DLI increased from 1.2 to 12.3 $mol \cdot m^{-2} \cdot d^{-1}$, the RDM of argyranthemum ‘Madeira Cherry Red’

(*Argyranthemum frutescens*), diascia ‘Wink Coral’, nemesia ‘Aromatica Royal’ (*Nemesia fruticans*), osteospermum ‘Voltage Yellow’ (*Osteospermum ecklonis*), scaevola ‘Blue Print’ (*Scaevola hybrid*), and sutera ‘Abunda Giant White’ (*Sutera cordata*) cuttings also increased 14 d after transfer (Currey et al., 2012). Additionally, increases in the RDM and SDM of New Guinea impatiens ‘Celebration Pink’, geranium ‘Fantasia Dark Red’, and petunia ‘Suncatcher Midnight Blue’ cuttings occurred 14 d after transferring as DLI increased from 2.0–2.4 to 13.0–14.2 $mol·m^{-2}·d^{-1}$ (Currey and Lopez, 2015).

In this study, genera-specific DLIs were identified, with the highest RDM of sage, spearmint, and rosemary occurring at 16.4 $mol·m^{-2}·d^{-1}$, oregano at 12.1 $mol·m^{-2}·d^{-1}$, and thyme at 13.9 $mol·m^{-2}·d^{-1}$ (Fig. 1C-D). Additionally, at a DLI of 16.4 $mol·m^{-2}·d^{-1}$, the SDM and TDM of oregano and spearmint were the greatest whereas the SDM of rosemary, sage, and thyme were greatest at 14.5, 12.5, and 13.2 $mol·m^{-2}·d^{-1}$ (Fig. 1E-H). Although these genera-specific DLIs were high for this study, DLIs of 11.2 to 16.4 $mol·m^{-2}·d^{-1}$ are categorized as medium-light during finishing (Faust, 2011). Additionally, the SDM of hydroponically grown mint, oregano, and thyme increased as the DLI increased to 20 $mol·m^{-2}·d^{-1}$, while the SDM of sage increased to a DLI of 15.9 $mol·m^{-2}·d^{-1}$ (Litvin-Zabal, 2019). Similarly, Walters (2020) also reported the SDM of hydroponically grown sage ‘Extrakta’, and spearmint ‘Spanish’ to increase as DLI increased from 6 to 18 $mol·m^{-2}·d^{-1}$. Furthermore, Litvin-Zabal (2019) classified hydroponically grown mint and sage as medium-light plants during finishing which had optimal DLIs of 19.0 and 14.8 $mol·m^{-2}·d^{-1}$, respectively. Whereas, oregano and thyme were reported to be possible high to very high-light plants because their optimal DLIs were ≥20 $mol·m^{-2}·d^{-1}$ (Litvin-Zabal, 2019). Not surprisingly, the greatest oregano, sage, spearmint, and thyme RDM, SDM, and TDM of were under DLIs of 11.2–16.4 $mol \cdot m^{-2} \cdot d^{-1}$, which is lower than the optimum DLI for these crops at finishing (Litvin-Zabal, 2019; Walters, 2020).

The R:S of oregano, spearmint, and thyme was greatest at DLIs generally lower than those for high RDM, SDM, and TDM, most likely due to small SDM accumulation at lower DLIs (Fig. 1G-H). For example, the R:S of spearmint was greatest at an optimal DLI of 12.1 $mol \cdot m^{-2} \cdot d^{-1}$ but the optimal DLI for RDM and SDM was 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ or above the studied range (Fig. 1G). Even though a DLI of 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ influenced greater accumulation of RDM, SDM, and TDM, the R:S indicates that the cutting is allocating more energy into the roots at a lower DLI, which is more desirable for young plants (Currey et al., 2012). This is in agreement with previous research with New Guinea impatiens ‘Magnum Salmon’, which had a higher TDM under a DLI of 15.6 $mol \cdot m^{-2} \cdot d^{-1}$ but had a slightly greater R:S under a DLI of 8.5 $mol \cdot m^{-2} \cdot d^{-1}$ after 14 d (Currey and Lopez, 2012). Thus, it may be possible that higher DLIs (>16.4 $mol \cdot m^{-2} \cdot d^{-1}$) may not be necessary to produce a high-quality culinary herb liner as we had originally hypothesized.

Stem length of oregano, spearmint, and thyme generally decreased as DLI increased (Fig. 2A). Decreasing stem length with increasing DLI has also been reported for seedlings of impatiens ‘Accent Red’ (*Impatiens walleriana*), salvia ‘Vista Red’ (*Salvia splendens*) (Pramuk and Runkle, 2005), cuttings of angelonia ‘AngelMist White Cloud’ (*Angelonia angustifolia*), osteospermum ‘Voltage Yellow’ (Hutchinson et al., 2012), and finished yarrow ‘Red Velvet’ (*Achillea millefolium*), wandflower ‘Siskiyou Pink’ (*Gaura lindheimeri*), and lavender ‘Hidcote Blue’ (Fausey et al., 2005).

However, stem length of rosemary and sage were not influenced by DLI, thus it is possible that stem length may be more genera-dependent than DLI dependent. This has also been identified for liners of New Guinea impatiens 'Celebration Pink', geranium 'Fantasia Dark Red', and petunia 'Suncatcher Midnight Blue' despite increasing stem lengths, DLI was insignificant (Currey and Lopez, 2015). Furthermore, it is possible that the negligible difference in the stem length of sage and rosemary was observed due to the short length of the experiment. For example, sage grown for 84 d under a DLI of 9.2 $mol \cdot m^{-2} \cdot d^{-1}$ was more compact (12.1 cm) compared to lower DLIs of 3.1 (28.5 cm), 4.5 (22.7 cm), and 6.5 $mol \cdot m^{-2} \cdot d^{-1}$ (20.3 cm) (Mapes and Xu, 2014). Additionally, the height of hydroponically grown sage 'Extrakta' and spearmint 'Spanish' had no consistent trends with DLIs ranging from 6 to 18 $mol \cdot m^{-2} \cdot d^{-1}$ at 14 to 28 d after transplant (Walters, 2020).

For all culinary herbs studied, the stem caliper increased as DLI increased to genera-specific maximums of 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ for oregano, spearmint, and rosemary, and 14.8 and 10.8 $mol \cdot m^{-2} \cdot d^{-1}$ for sage and thyme, respectively (Fig. 2C-D). The stem caliper of yellow elder 'Mayan Gold' (*Tecoma stans*) seedlings after 35 d of propagation increased by 133% as DLI increased from 0.8 to 25.2 $mol \cdot m^{-2} \cdot d^{-1}$ (Torres and Lopez, 2011). Similarly, as DLI increased from 2.0 to 13.4 $mol \cdot m^{-2} \cdot d^{-1}$, the stem caliper of New Guinea impatiens 'Celebration Pink' increased by 26% after 14 d of treatments but did not influence the stem caliper of geranium 'Fantasia Dark Red' or petunia 'Suncatcher Midnight Blue' (Currey and Lopez, 2015).

The SQ for all culinary herbs was similar to stem length, and generally decreased with increasing DLI (Fig. 2E-F). This was expected since the SQ is stem length divided by the stem caliper and taller stems and smaller calipers were recorded under lower DLIs. In contrast, Currey et al. (2012) found the SQ of nemesia 'Aromatica Royal' increased by 58% as DLI increased from 1.2 to 12.3 $mol \cdot m^{-2} \cdot d^{-1}$ during propagation while angelonia 'AngelMist White Cloud', diascia 'Wink Coral', lantana 'Lucky Gold' (*Lantana camara*), scaevola 'Blue Print', sutera

‘Abunda Giant White’, and verbena ‘Aztec Violet’ (*Verbena ×hybrida*) were unaffected by DLI. Thyme SQ was influenced by DLI more than other genera measured, decreasing by 53% as DLI increased from 2.8 to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ (Fig. 2E). This is largely due to the small stem caliper and upright habit of thyme; thus, the SQ may not be a good measurement to assess the quality of young culinary herbs.

Despite contrasting SQ results from the present study to previous studies, the QI of all culinary herbs showed similar results to other young plants. The QI is an integrative approach to assessing young plant quality by using the TDM, R:S, and SQ; with larger QIs being equivalent to high-quality plants (Currey et al., 2013). From this current study, all culinary herb liners had high QIs at DLI optimums ranging from 10.4 to 16.4 $mol \cdot m^{-2} \cdot d^{-1}$ dependent upon genera (Fig. 2 G-H). Currey et al. (2012) reported increasing QIs as the DLI increased from 1.2 to 12.3 $mol \cdot m^{-2} \cdot d^{-1}$ for argyranthemum ‘Madeira Cherry Red’, diascia ‘Wink Coral’, nemesia ‘Aromatica Royal’, osteospermum ‘Voltage Yellow’, and sutera ‘Abunda Giant White’, whereas the QI of angelonia ‘AngelMist White Cloud’ and lantana ‘Lucky Gold’ were greatest at DLIs of 10.6 and 7.2 $mol \cdot m^{-2} \cdot d^{-1}$, respectively. Additionally, the QI of yellow elder ‘Mayan Gold’ increased by roughly 26-fold as DLI increased from 0.8 to 25.2 $mol \cdot m^{-2} \cdot d^{-1}$ (Currey et al., 2013). Although the specific QI outlined in this study was not used, Fausey et al. (2005) used a quality rating on a scale of 1 (prostrate habit, poor lateral branching) to 5 (upright habit, extensive lateral branching) and found the quality of yarrow ‘Red Velvet’, wandflower ‘Siskiyou Pink’, and lavender ‘Hidcote Blue’ increased to ratings of 4 to 5 as DLI increased from 5 to 20 $mol \cdot m^{-2} \cdot d^{-1}$. It is supported by our study and previous studies that the QI increases as DLI increases, but to genera-specific DLI optimums.

Although not measured, the overall visible appearance of the culinary herb liners propagated under DLIs of 11.2 to 16.4 mol·m^{-2}·d^{-1} is worth mentioning. Liners of sage and spearmint developed small (≤1 mm) necrotic lesions on the adaxial surface of leaves, however, new growth from these liners once transplanted into a common environment with a DLI of 17 and 12 mol·m^{-2}·d^{-1}, respectively, were unaffected. Furthermore, from the collective results, the culinary herbs in this study can benefit from DLIs between 10 to 12 mol·m^{-2}·d^{-1} without sacrificing plant quality and higher DLIs are not necessary as we previously hypothesized. Additionally, achieving DLIs >15 mol·m^{-2}·d^{-1} may not be possible for producers in Northern latitudes, especially if young culinary herbs are propagated during late winter and early spring, where unnecessary energy cost would be inquired from supplemental lighting.

Conclusion

A DLI between 10 to 12 mol·m^{-2}·d^{-1} resulted in the highest quality culinary herb liners. We determined that quality of oregano, rosemary, sage, spearmint, and thyme rooted cuttings under DLIs ≥15 mol·m^{-2}·d^{-1} was reduced due to genera-specific decreases in TDM, SQ, QI, and appearance of necrotic lesions. We also determined that rooting of culinary herbs can be shorter than herbaceous ornamental cuttings; 2 weeks for oregano and spearmint, 3 weeks for sage and thyme, and at least 4 weeks for rosemary to produce a pullable liner. However, culinary herbs can be propagated under similar environmental conditions to ornamental cuttings.

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APPENDIX

Table IV-1. Percent shade, daily light integral (DLI), root-zone, plant, and air temperatures, and vapor-pressure deficit (VPD) for callusing and post-callusing during propagation treatments.

Date	Shade (%)	DLI ($mol \cdot m^{-2} \cdot d^{-1}$)	Temperature (°C) Root-zone	Plant	Air	VPD (kPa)
			Callus			
09 Sept. 2019	56	4.3 ± 0.5	22.1 ± 2.9	26.4 ± 2.2	23.3 ± 3.9	0.4 ± 0.3
03 Oct. 2019	56	4.6 ± 0.7	23.4 ± 2.1	26.0 ± 1.7	23.0 ± 1.9	0.3 ± 0.1
07 Jan. 2020	56	4.8 ± 0.2	22.0 ± 0.8	26.1 ± 0.7	23.8 ± 0.5	0.3 ± 0.2
			Post-callus			
09 Sept. 2019	0	16.4 ± 2.9	23.1 ± 3.5	27.0 ± 3.2	23.4 ± 3.7[z]	0.4 ± 0.3[z]
	36	9.4 ± 1.8	23.5 ± 3.2	25.1 ± 3.4	–[y]	–
	56	5.8 ± 0.8	23.9 ± 2.8	24.9 ± 3.4	–	–
	76	3.1 ± 0.2	22.4 ± 2.8	25.0 ± 2.8	–	–
03 Oct. 2019	0	12.3 ± 1.3	24.2 ± 2.8	27.0 ± 2.3	24.2 ± 1.3[z]	0.3 ± 0.2[z]
	36	8.9 ± 1.5	24.9 ± 1.6	25.1 ± 2.0	–	–
	56	5.4 ± 0.7	24.1 ± 1.7	25.6 ± 1.6	–	–
	76	2.9 ± 0.4	24.1 ± 1.6	25.3 ± 1.7	–	–
07 Jan. 2020	0	11.2 ± 0.7	23.2 ± 1.1	27.0 ± 1.8	23.9 ± 0.5[z]	0.3 ± 0.1[z]
	36	6.2 ± 0.3	23.4 ± 1.7	26.0 ± 1.4	–	–
	56	4.0 ± 0.2	22.2 ± 0.7	24.7 ± 1.1	–	–
	76	2.8 ± 0.2	23.7 ± 0.7	23.8 ± 2.5	–	–

[z]Averaged between two propagation houses.

[y]Air and VPD were the same.

Table IV-2. Regression equations for root, shoot, and total dry mass, root-to-shoot ratio, stem length, stem caliper, sturdiness quotient and quality index for five culinary herb liners. The x is the daily light integral (DLI) and plots for equations are in Fig. 1 and 2.

Genera	Parameter	Regression equation	Optimal DLI
Oregano	Root dry mass	$y = 6.26 + 3.94x – 0.14x^2$	12.1
	Shoot dry mass	$y = 55.8 + 6.93x$	
	Total dry mass	$y = 70.34 + 8.34x$	
	Root:shoot ratio	$y = 0.15 + 0.025x – 0.0013x^2$	9.6
	Stem length	$y = 8.55 – 0.16x$	
	Stem caliper	$y = 1.65 + 0.034x$	
	Sturdiness quotient	$y = 5.14 – 0.16x$	
	Quality index	$y = 253.54 + 69.17x – 3.17x^2$	10.9
Rosemary	Root dry mass	$y = -3.78 + 4.14x – 0.094x^2$	–[z]
	Shoot dry mass	$y = 64.71 + 10.16x – 0.35x^2$	14.5
	Total dry mass	$y = 60.92 + 14.3x – 0.44x^2$	16.3
	Root:shoot ratio	$y = 0.012 + 0.028x – 0.0007x^2$	–
	Stem length		
	Stem caliper	$y = 1.55 + 0.035x$	
	Sturdiness quotient	$y = 3.4 – 0.056x$	
	Quality index	$y = 248.98 + 32.67x – 1.06x^2$	15.1
Sage	Root dry mass	$y = 1.63 + 3.84x$	
	Shoot dry mass	$y = 44.28 + 39.13x – 1.56x^2$	12.5
	Total dry mass	$y = 39.84 + 44.78x – 1.66x^2$	13.5
	Root:shoot ratio	$y = 0.049 + 0.012x$	
	Stem length		
	Stem caliper	$y = 2.25 + 0.21x – 0.0097x^2$	10.8
	Sturdiness quotient	$y = 2.36 – 0.18x + 0.0081x^2$	11.1
	Quality index	$y = 260.36 + 22.15x$	
Spearmint	Root dry mass	$y = -2.43 + 6.73x – 0.16x^2$	–
	Shoot dry mass	$y = 66.27 + 7.53x$	
	Total dry mass	$y = 73.31 + 11.43x$	
	Root:shoot ratio	$y = 0.029 + 0.058x – 0.0024x^2$	12.1
	Stem length	$y = 10.67 – 0.61x + 0.024x^2$	12.7
	Stem caliper	$y = 1.78 + 0.042x$	
	Sturdiness quotient	$y = 6.39 – 0.53x + 0.02x^2$	13.3
	Quality index	$y = 466.32 + 20.53x$	
Thyme	Root dry mass	$y = -3.42 + 2.28x – 0.082x^2$	13.9
	Shoot dry mass	$y = 3.01 + 7.91x – 0.3x^2$	13.2
	Total dry mass	$y = -0.41 + 10.19x – 0.38x^2$	13.4
	Root:shoot ratio	$y = -0.0061 + 0.043x – 0.0017x^2$	12.6
	Stem length	$y = 17.25 – 0.26x$	
	Stem caliper	$y = 0.53 + 0.071x – 0.0024x^2$	14.8
	Sturdiness quotient	$y = 25.25 – 0.89x$	
	Quality index	$y = 222.87 + 163.46x – 7.89x^2$	10.4

[z]Optimal DLI calculated outside of studied range.

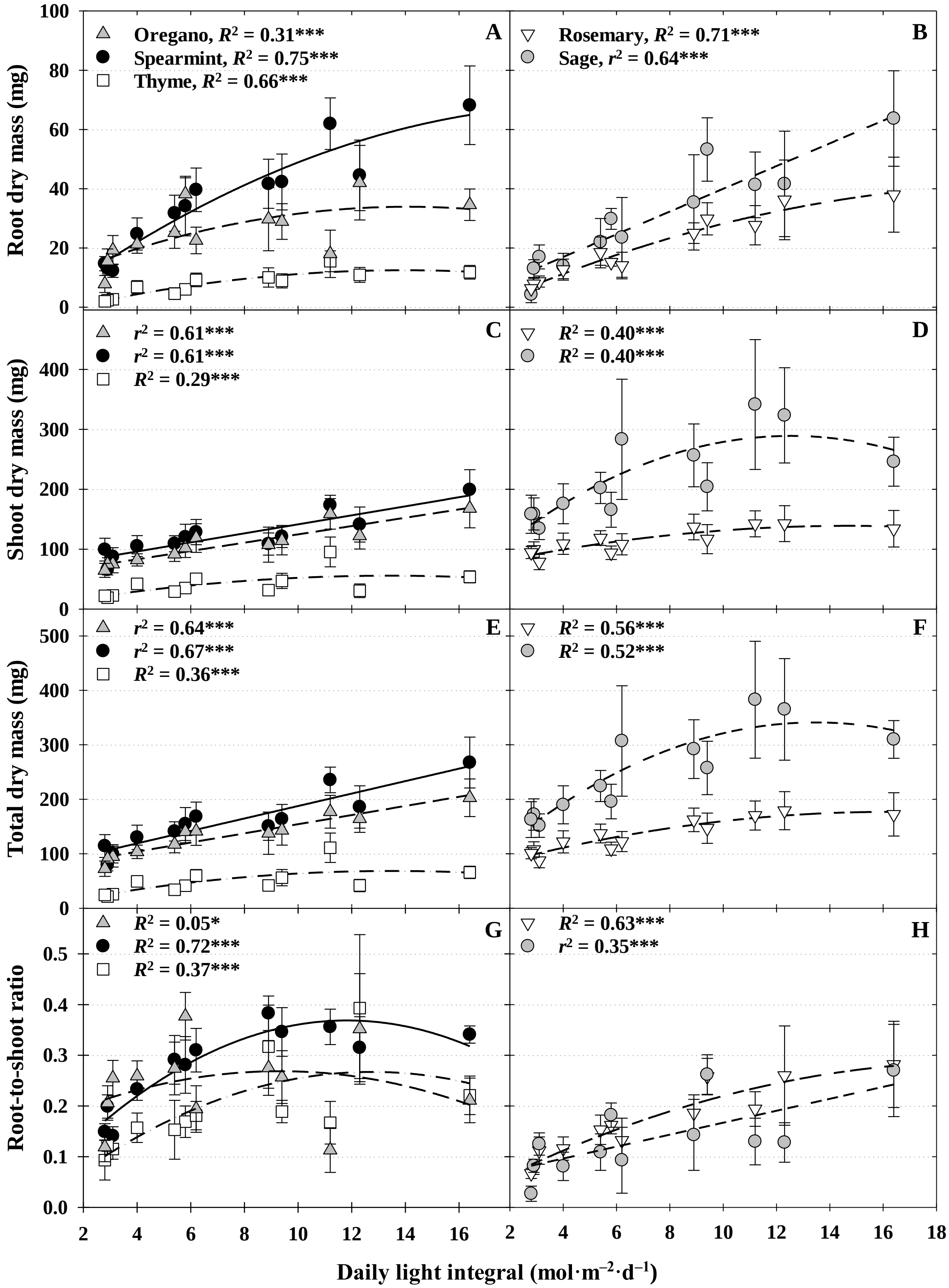

Figure IV-1. The root dry mass, shoot dry mass, total dry mass, and root-to-shoot ratio for liners of oregano, rosemary, sage, and thyme after 16 d and spearmint after 9 d of daily light integral treatments. Each symbol represents the mean of 10 plants and error bars represent SEs of the mean. Regression lines are presented with corresponding r^2 and R^2 presented. * and *** indicates significant at $P \leq 0.05$ or 0.001, respectively.

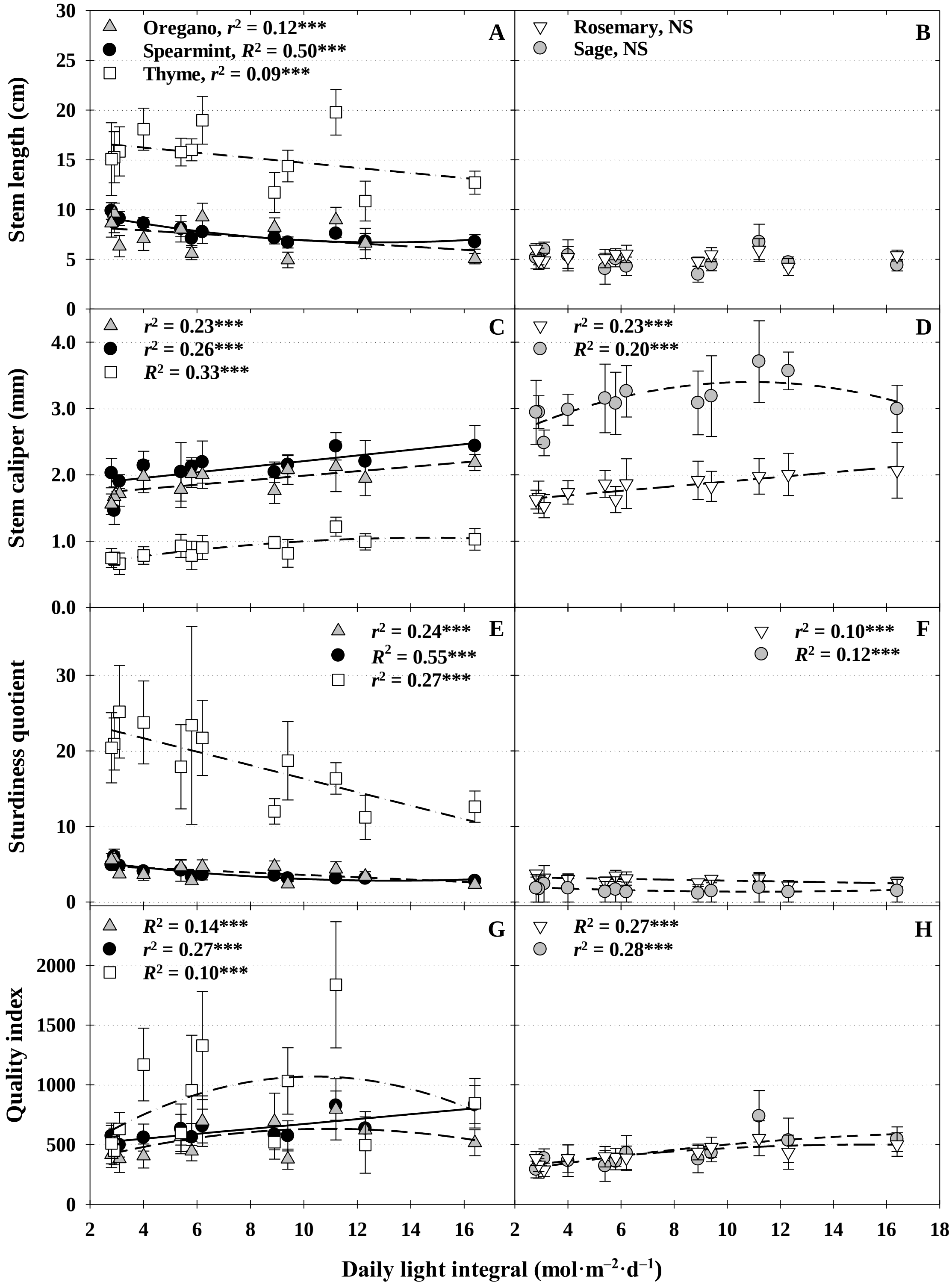

Figure IV-2. The stem length, stem caliper, sturdiness quotient, and quality index for liners of oregano, rosemary, sage, and thyme for 16 d and spearmint for 9 d of daily light integral treatments. Each symbol represents the mean of 10 plants and error bars represent SEs of the mean. Regression lines are presented for significant correlations only with corresponding r^2 and R^2 presented. NS and *** indicates nonsignificant or significant at $P \leq 0.001$, respectively.

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