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Photosynthetic Daily Light Integral Influences Growth, Morphology, Physiology, and Quality of Swordfern Cultivars

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Abstract. **Boston and Australian swordferns (*Nephrolepis* sp.) are popular tropical ferns for hanging baskets and containers; however, greenhouse production occurs during times of the year when growers may need to deploy shade or supplemental lighting to manage the growing environment. Our objectives were to quantify the impact of the daily light integral (DLI) on growth, morphology, physiology, and ornamental quality of containerized *Nephrolepis* species and cultivars, and to establish optimal DLIs for containerized swordferns to assist commercial greenhouse growers with light management strategies during production. Eleven cultivars of Boston swordfern [*N. exaltata* (L.) Schott Blue Bells, Compacta, Fluffy Ruffles, Gold, Montana, Nevada, Petticoat, Pom Pom, Super, Tiger, and True] and one cultivar of Australian swordfern [*N. obliterata* (R. Br.) J. Sm. Western Queen] were investigated. Plants were grown for 58 days at 20 °C and placed under one of four different fixed-woven shadecloths providing ≈86%, 62%, 42%, or 26% shade or no shade, thereby establishing mean DLIs of 3.2, 6.4, 10.7, 12.4, and 17.1 mol·m^{-2}·d^{-1}, respectively. For most cultivars, the growth index, which is an integrated measurement of height and diameter, decreased linearly as the DLI increased from 3.2 to 17.2 mol·m^{-2}·d^{-1}, resulting in smaller compact plants. Increasing the DLI significantly affected the frond number of each cultivar differently, whereas dry mass generally increased as the DLI increased from 3.2 to 10.7 to 12.4 mol·m^{-2}·d^{-1} for most cultivars. For each cultivar, as the DLI increased from 3.2 to 17.1 mol·m^{-2}·d^{-1}, the chlorophyll concentration index decreased, whereas the hue angle increased and chroma was unaffected. Our results indicate that growers should maintain ≈10 to 12 mol·m^{-2}·d^{-1} during greenhouse *Nephrolepis* production; however, DLIs ≥5.5 mol·m^{-2}·d^{-1} and ≤16.5 mol·m^{-2}·d^{-1} also improved the quality of some *Nephrolepis* cultivars.**

In the past decade, tropical ferns have increased in popularity for use in hanging baskets or as a potted indoor crop. From 2009 to 2019, the total sales value of tropical ferns increased by 21% ($9.8 million US) (US Department of Agriculture, 2010, 2020). To date, tropical ferns are the second largest (14%) category of the foliage plant sector in the commercial floriculture industry in the United States, with a reported volume of 12 million containers (hanging baskets and pots) representing a total sales value of $67.2 million US (US Department of Agriculture, 2020). Although there are more than 120 tropical fern species available from commercial propagators (ARC Ferns, Inc., 2022; Casa Flora, Inc., 2022), cultivars of Boston and Australian swordferns (*Nephrolepis* sp.) are the most common taxa grown by greenhouse growers for hanging basket or container production.

From liners (young plants), the production cycle for Boston swordfern cultivars requires 8 to 12 months. In general, production begins in June, when liners are transplanted to small containers for bulking. During this time, the ambient outdoor daily light integral (DLI) is 35 to 65 mol·m^{-2}·d^{-1} (Faust and Logan, 2018); however, growers may need to deploy shade curtains to manage greenhouse temperatures, consequently reducing the DLI by 40% to 80% (Faust et al., 2005). Furthermore, the DLI inside the greenhouse can be reduced by 50% or more from the greenhouse infrastructure, glazing material, and overhead hanging baskets (Faust et al., 2005; Hanan, 1998; Peet, 1999; Wilson et al., 1992). In fall, bulked plants are typically transplanted to larger containers or hanging baskets for subsequent growth and finishing during winter and early spring months. The DLIs during the growth and finishing stages of production can be as low as 5 to 10 mol·m^{-2}·d^{-1} (Faust and Logan, 2018), especially across the northern United States (lat. ≥40° N) (Owen, 2017). Additionally, Boston sword fern hanging baskets can be suspended under single or multiple layers when growers need to balance a maximum DLI at the top layer of hanging baskets and minimum DLI at the bottom layer of hanging baskets. Recent observations found that the DLI was ≤5 mol·m^{-2}·d^{-1} for underlying layers of Boston swordfern hanging baskets in a multiple-layer hanging basket system, and that containerized swordfern crops were grown at bench-level and floor-level during finishing (personal observation). These low-light conditions are problematic because most bedding plants are considered to have excellent quality when the DLI is 15 to 20 mol·m^{-2}·d^{-1} during the finishing stage of production; however, most greenhouses growers will provide a minimum acceptable DLI of 8 to 12 mol·m^{-2}·d^{-1}, resulting in bedding plants with fair to good quality (Lopez and Currey, 2021).

Numerous studies have described the effect of the DLI on the growth, development, morphology, and physiology of annual bedding plants (Blanchard et al., 2011; Faust et al., 2005; Garland et al., 2010; Hutchinson, 2012; Mattson and Erwin, 2005; Moccaldi and Runkle, 2007; Owen and Lopez, 2018; Owen et al., 2018; Pramuk and Runkle, 2005), flowering herbaceous perennials (Fausey et al., 2005; Garland et al., 2012; Warner and Erwin, 2003), potted flowering plants (Christiaens et al., 2014; Currey and Erwin, 2011; Karlsson, 2002; Oh et al., 2009), and, to a lesser extent, ornamental foliage crops (Nam et al., 1997; Pennisi et al., 2005, Shen and Seeley, 1983; Stamps, 1995; Vladimirova et al., 1997; Yeh and Wang, 2015). In general, increasing the DLI increases the biomass accumulation, hastens development, and improves the final plant quality of many floriculture crops (Oh et al., 2009); however, there is a significant amount of variation among taxa regarding DLI requirements (Currey and Erwin, 2011; Faust et al., 2005; Hutchinson, 2012). For instance, across taxa, Faust et al. (2005) reported increased total dry mass for ageratum (*Ageratum houstonianum* L.), marigold *(Tagetes erecta* L.), petunia (*Petunia ×hybrida* Juss.), salvia (*Salvia coccinea* L.), vinca (*Catharanthus roseus* L.), and zinnia (*Zinnia elegans* L.), but not for begonia (*Begonia ×semperflorens-cultorum* L.) and impatiens (*Impatiens walleriana* L.) when plants were grown under increasing DLIs from 5 to 43 mol·m^{-2}·d^{-1}. Large variations within taxa also occur. For instance, shoot heights of glaucous kalanchoe (*K. glaucescens*) and common kalanchoe (*K. rotundifolia*) increased as the DLI increased from 4.3 to 8.6 mol·m^{-2}·d^{-1}, whereas the shoot height of shovel leaf kalanchoe (*K. nyikae*) decreased

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as the DLI increased from 4.3 to 17.2 mol·m^{-2}·d^{-1}; however, shoot heights of Christmas tree plant (*K. laciniata*), chandelier plant (*K. manginii*), and velvet leaf kalanchoe (*K. velutina*) were unaffected by increasing DLI (Currey and Erwin, 2011). Furthermore, as the DLI increased, differences among kalanchoe species were observed for node numbers below the terminal inflorescence and time to first open flower, whereas time to flower and shoot dry weight gain increased for all species. Although these studies aid in the understanding of floriculture crop responses to DLI, many reported that the maximum plant response to the DLI was also the maximum DLI treatment provided during the experiment; furthermore, the optimal DLI was not identified because the response never reached a plateau (optimal) or a supraoptimal DLI (Faust and Logan, 2018). Therefore, the objectives of this study were to quantify the impact of the DLI on growth, morphology, physiology, and ornamental quality of containerized *Nephrolepis* species and cultivars, and to establish the optimal DLI for containerized swordferns using plateau models to assist commercial greenhouse growers with light management strategies during production.

Materials and Methods

Plant material and culture. On 2 Jun 2021, 72-cell plug trays (30.7-mL individual cell volume) of 11 cultivars of Boston swordferns [*N. exaltata* (L.) Schott Blue Bells, Compacta, Fluffy Ruffles, Gold, Montana, Nevada, Petticoat, Pom Pom, Super, Tiger, and True] and one cultivar of Australian swordfern [*N. obliterata* (R. Br.) J. Sm. Western Queen] were received from a commercial supplier (ARC Ferns, LLC, Apopka, FL). On 9 Jun 2021, young plants of each cultivar with a similar size were selected and transplanted with one plant per 12.7-cm-diameter container (885-mL volume; ITML Horticultural Products, Middlefield, OH) filled with premoistened commercial soilless peat-based substrate comprising (by volume) 80% Canadian sphagnum peatmoss and 20% perlite and amended with calcitic and dolomitic limestones, wetting agent, and a starter nutrient charge (Pro-Line C/20; Jolly Gardener, Oldcastle Lawn and Garden, Inc., Atlanta, GA). Substrate chemical properties, including pH, electrical conductivity (EC), and nutrients were determined for three representative samples and analyzed by the University of Kentucky Division of Regulatory Services using procedures outlined by Warnke (2014). Substrate pH, EC, and nutrients (in mg·L^{-1}) before transplant were 6.0 pH, 1.2 mS·cm^{-1}, 59 nitrate–nitrogen (NO_3^-–N), 17.4 phosphorus (P), 91.8 potassium (K), 162 calcium (Ca), 74 magnesium (Mg), 7.1 iron (Fe), 1.9 manganese (Mn), 0.1 boron (B), 0.1 copper (Cu), 17.1 zinc (Zn), and 31.2 sodium (Na). Additionally, substrate physical properties were determined using six representative samples that were analyzed using the North Carolina State University Porometer Procedure (Fonteno et al., 1995). Physical properties of the substrate were (by volume) 21.6 ± 2.1% air space, 70.9 ± 1.1% total porosity, 49.3 ± 1.3% container capacity, and 0.22 ± 0.02 g·cm^{-3} bulk density.

Before transplanting, three representative tepid water samples were obtained and analyzed by the University of Kentucky Division of Regulatory Services using procedures outlined by Greenberg et al. (1992). Tepid water pH, EC, and nutrients (in mg·L^{-1}) at the first water irrigation were 7.9 pH, 0.26 mS·cm^{-1}, 3 NO_3^-–N, 0 P, 0.6 K, 24 Ca, 11 Mg, 0.1 Fe, 0 Mn, 0 B, 0 Cu, 0 Zn, and 10.4 Na. At time of transplanting, plants were irrigated to container capacity with tepid water supplemented with 93% sulfuric acid (H_2SO_4; Riverside Chemical Co., North Tonawanda, NY) delivered by a chemical injector (HN55 1:100 Chemilizer; Hydro Systems Co., Cincinnati, OH) at 2.13 mL·L^{-1} to neutralize alkalinity from 0.98 to 0.22 meq·L^{-1} bicarbonate (HCO_3^-) and reduce irrigation water pH from 7.9 to 5.8. During each subsequent irrigation, plants were irrigated with acidified tepid water prepared as previously described and supplemented with a water-soluble fertilizer (17 N–1.3 P–14.1 K Cal–Mag) (Peter's Professional Peat-Lite Neutral Cal-Mag; ICL Specialty Fertilizers-Americas, Summerville, SC) containing 4% ammoniacal (NH_4^+–N) and 13% nitrate (NO_3^-)–N delivered by an injector (D14MZ2 14 GPM Dosatron; Dostatron International, Clearwater, FL) to provide 180 mg·L^{-1} N. Three representative nutrient solution samples were obtained and analyzed by the University of Kentucky Division of Regulatory Services using procedures outlined by Greenberg et al. (1992). Plants received the following (in mg·L^{-1}): 184 N, 52.1 P, 218 K, 182 Ca, 77.1 Mg, 1.0 Fe, 0.7 Mn, 0.6 B, 0.5 Cu, 0.3 Zn, and 14.0 Na. The nutrient solution was delivered through five benchtop 1.2-cm black irrigation lines fitted with 1.89 L·h^{-1} pressure-compensated drip emitters (0.5 GPH Netafim Woodpecker JR PC Emitter; Netafim Irrigation, Inc., Fresno, CA) that were placed on top of the substrate of each container. Plants of each cultivar were placed on the same irrigation line, and each irrigation line was controlled independently. One drip emitter per irrigation line was inserted into a sealed 1.89-L black container to determine the volume of nutrient solution applied. Irrigation was controlled (Sterling 36; Superior Controls, Torrance, CA) and applied for 5 min daily beginning at 0900 HR. The average (mean ± *SD*) volume of nutrient solution applied across all irrigation lines throughout the 58-d duration of the experiment was 111.7 ± 30.7 mL.

DLI treatments. Shade structures (3.0 m × 1.5 m × 1.5 m) were constructed using 1.9-cm-diameter PVC pipe and covered with a fixed shadecloth providing ≈86%, 64%, 42%, or 25% shade (Solaro 8635-O-FB or Harmony 6420-O-E, 4215-O-FR, or 2047-FR; Ludvig Svensson, Inc., Charlotte, NC) or no shade (≈0%). Each shade structure was elevated 0.86-m above the greenhouse floor on expanded metal benches (6.0 m × 1.5 m) and oriented with a longitudinal axis running north–south. Each shade structure was replicated twice across the greenhouse. Four experimental units (individual plants) of each cultivar were randomly assigned and placed under each shade structure. Supplemental and day-extension lighting was provided by 660-W high-pressure sodium lamps (NXT-LP; P.L. Light Systems, Beamsville, ON, Canada) fitted with alpha reflectors (P.L. Light Systems) from 0600 to 2200 HR (16-h photoperiod) that delivered a supplemental photosynthetic photon flux density (*PPFD*) of ≈20, 53, 69, 95, or 138 μmol·m^{-2}·s^{-1} at plant height as measured with a quantum sensor (LI-250A light meter; LI-COR Biosciences, Lincoln, NE) under ≈86%, 62%, 42%, 26%, and 0% shade, respectively. High-pressure sodium lamps were controlled by an environmental computer (Titan 1.0; Argus Control Systems Ltd., Surrey, British Columbia, Canada). They were turned on when the outdoor light intensity decreased to less than ≈250 μmol·m^{-2}·s^{-1}. They were turned off when the outdoor light intensity reached ≈500 μmol·m^{-2}·s^{-1}. Retractable woven shade curtains (OLS 50; Ludvig Svensson Inc.) were deployed when the outdoor light intensity reached ≈750 μmol·m^{-2}·s^{-1}; they were retracted when the outdoor light intensity decreased to less than ≈500 μmol·m^{-2}·s^{-1}. The average (mean ± *SD*) DLIs established under ≈86%, 62%, 42%, 26%, and 0% shade throughout the 58-d duration of the experiment for block 1 were 3.2 ± 0.5, 6.5 ± 0.9, 10.9 ± 1.4, 12.4 ± 1.5, and 17.2 ± 2.1 mol·m^{-2}·d^{-1}; for block 2, the DLIs were 3.3 ± 0.5, 6.4 ± 0.9, 10.4 ± 1.8, 12.4 ± 1.6, and 17.2 ± 2.3 mol·m^{-2}·d^{-1}.

Greenhouse environment. Plants were grown in a double polyethylene-covered greenhouse (16.5 m × 7.3 m) at the University of Kentucky Horticulture Research Farm, Lexington, KY (lat. 38° N, long. 84° W, 298 m above sea level) equipped with exhaust fans, evaporative pad cooling, horizontal air flow fans, retractable shade curtains, and natural gas heating controlled by an environmental computer (Titan 1.0; Argus Control Systems Ltd.). The greenhouse air temperature and relative humidity setpoints were 20 °C and 70%. A thermocouple enclosed in an aspirated radiation shield recorded greenhouse air temperature every 30 s, and they averages were logged every 15 min by a data logger (WatchDog Model 2475 Plant Growth Station; Spectrum Technologies, Inc., Aurora, IL). The average greenhouse air temperature and relative humidity throughout the 58-d duration of the experiment were 22.2 ± 3.5 °C and 69.3 ± 2.3%, respectively. Under each shade structure, full-spectrum quantum sensors (SS-500; Apogee Instruments, Logan, UT) measured the *PPFD* at the top of the plant canopy. Measurements were recorded every 15 s, and the average of each sensor was logged every 15 min by a data logger (Model CR1000; Campbell Scientific, Inc., Logan, UT) equipped with a 32-channel relay multiplexer (AM16/32B; Campbell Scientific, Inc.).

Data collection and calculations. Growth and morphological data were collected 58 d after transplanting on all experimental units (individual plants) of each cultivar grown under each DLI treatment. Plant height was determined by measuring from the substrate

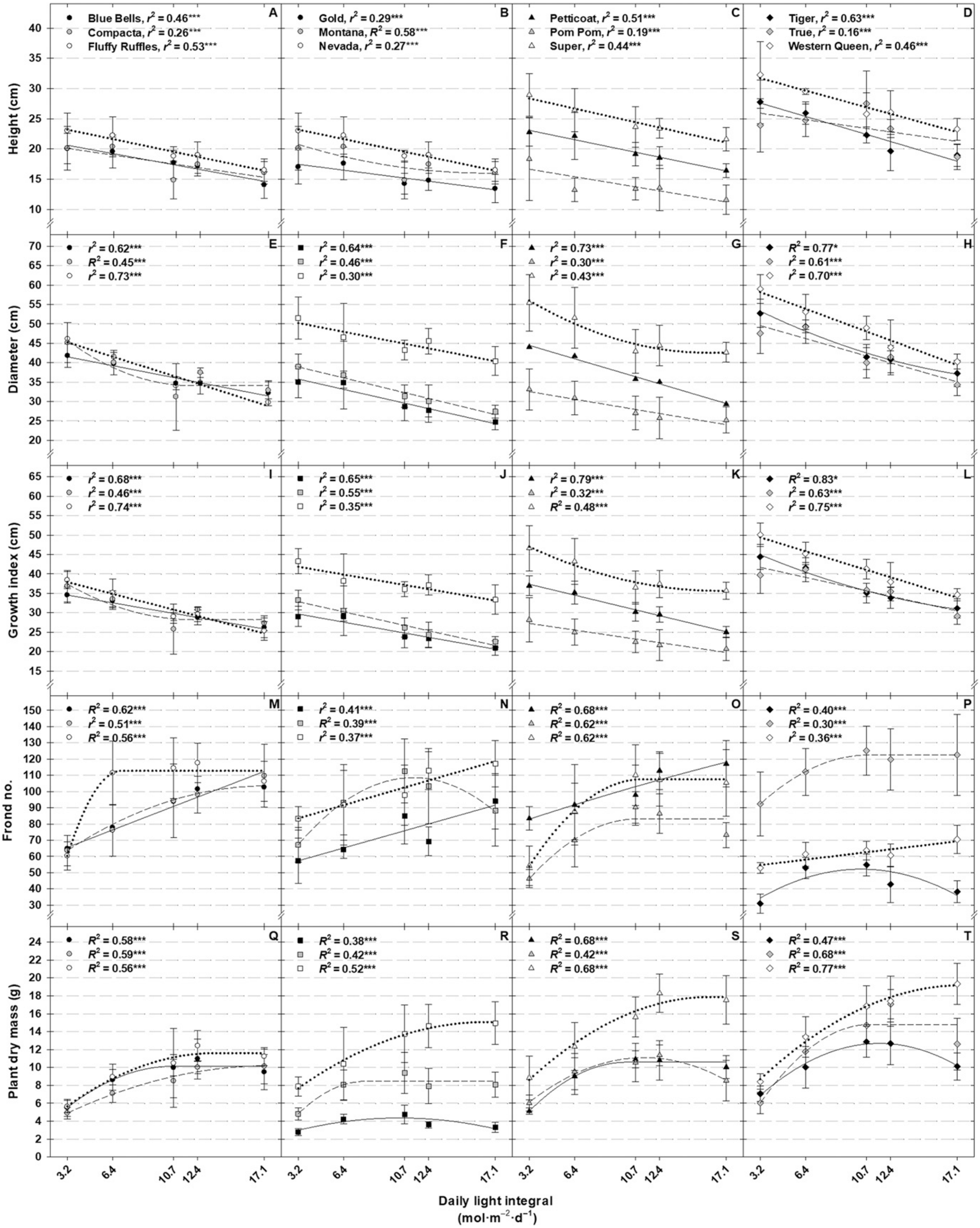

Fig. 1. Linear, quadratic, and nonlinear plateau regression models for average height (**A**–**D**), diameter (**E**–**H**), growth index (**I**–**L**), frond number (**M**–**P**), and plant dry mass (**Q**–**T**) of 11 cultivars of Boston swordfern [*Nephrolepis exaltata* (L.) Schott Blue Bells, Compacta, Fluffy Ruffles, Gold, Montana, Nevada, Petticoat, Pom Pom, Super, Tiger, and True] and one cultivar of Australian swordfern [*N. obliterata* (R. Br.) J. Sm. Western Queen] at 58 d after transplanting. Plants were grown under fixed shadecloth providing ≈86%, 62%, 42%, or 26% shade or no shade (≈0%) from ambient solar light and day-extension and supplemental lighting from high-pressure sodium lamps delivering ≈20, 53, 69, 95, or 138 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 16 h (0600–2200 HR), thereby establishing average photosynthetic daily light integrals of 3.2, 6.4, 10.7, 12.4, and 17.1 $mol \cdot m^{-2} \cdot d^{-1}$. Each symbol represents a mean of eight samples, and error bars represent ± *SE*. For each model, the corresponding r^2 (linear) or R^2 (quadratic and nonlinear plateau) values and significance at $P \leq 0.05$ (*) or 0.0001 (***) are presented.

surface to the highest frond apex. Plant diameter was determined by measuring the widest dimension and the axis perpendicular to the widest dimension and averaging. The growth index (GI) [GI = (plant height + plant diameter) ÷ 2] was calculated for each plant.

Chlorophyll (a+b) concentration indices (CCIs) of pinnules were estimated using three recently mature fronds of each plant using a chlorophyll content meter (MC-100; Apogee Instruments, Inc., Logan, UT) with a 20-mm^2 sampling area and two light-emitting diode light sources (653 nm and 931 nm). Measurements were performed on each cultivar in the greenhouse between 0900 and 1200 HR, and they were organized by sample across DLI and time to reduce time-of-day effects. Measurements were recorded and averaged across plant samples.

Using the same pinnules from three recently mature fronds previously mentioned for CCI, the pinnule color of each plant was measured using a portable tristimulus colorimeter (CR-200; Konica Minolta Sensing, Inc.) equipped with a measuring head with a self-contained light source that provided diffuse, uniform light over an 8-mm-diameter measuring area. The analyzer was calibrated to a standard white reflective plate ($L^* = 97.5$, $a^* = 0.40$, $b^* = 1.90$) using the CIE (Commission Internationale de l'Eclairage) 1976 ($L^*a^*b^*$) color coordinates. Chromametric a^* values [ratio between greenness and redness (green: $a^* = -60$; red: $a^* = +60$)] and chromametric b^* values [ratio between blueness and yellowness (blue: $b^* = -60$; yellow: $a^* = +60$)] were determined and used to calculate chroma (C^*) and hue angle ($h°$). Chroma is a measure of saturation and was calculated as follows:

$$C^* = \sqrt{a^{*2} + b^{*2}} \qquad [1]$$

On a circular scale, $h°$, or tone, indicates redness (0°), yellowness (90°), greenness (180°), or blueness (270°), and was calculated as follows:

$$h° = \tan^{-1}(b^*/a^*) \qquad [2]$$

On termination, one recently mature, fully expanded, and uncurled frond (stipe and blade) was removed by excising the stipe at the crown for each plant. Each frond was individually bagged and stored in a cooler at 7.2 °C before being transferred to a laboratory to determine the frond leaf area (FLA) by scanning each frond through a leaf-area meter (LI-3000; LI-COR) three times and averaging the results. The remaining plant tissues were destructively harvested by severing stipes from crowns or rhizomes at the substrate surface. All fronds, including fiddleheads, i.e., croziers, were counted and recorded for each plant to determine the frond number. All plant material, including fronds used to determine the FLA, were individually bagged, and dried in an oven at 70 °C. After 1 week, the dried plant material was weighed (MBS-600; Brecknell Scales USA, Fairmont, MN) to determine the plant dry mass (PDM).

Experimental design and statistical analyses. The experiment had a randomized complete block design with two blocks and five DLIs. The DLI treatments were randomized across the greenhouse, and plants of each cultivar were randomized under each DLI but placed on the same irrigation drip line. There were four experimental units per cultivar per DLI per block. Data of each cultivar were analyzed independently. Within each block, no significant differences occurred; therefore, data were pooled and DLIs were averaged across blocks, resulting in DLIs of 3.2 ± 0.5, 6.4 ± 1.0, 10.7 ± 1.6, 12.4 ± 1.6, and 17.1 ± 2.3 mol·m^{-2}·d^{-1}. Effects of DLI per cultivar were analyzed using SAS (version 9.4; SAS Institute, Cary, NC) general linear model procedure (PROC GLM) for the analysis of variance. For each cultivar, regression analyses of plant height, diameter, GI, frond number, PDM, CCI, L^*, C^*, and $h°$ (dependent variables) were performed using SAS regression procedure (PROC REG) to determine the best fit linear (L) and quadratic (Q) models. Additionally, data were analyzed using nonlinear regression (PROC NLIN) to determine the best fit quadratic plateau models (QP) for each dependent variable. Quadratic and QP models were compared based on the highest R^2 value and significance. For QP models, the reported X_0 value provided for each dependent variable indicated the DLI at which the model reached a maximum value and no additional increase in DLI resulted in an increase of the dependent variable. Equations, models, and expanded methods for statistical analyses were reported by Henry (2017). For all analyses, $P \leq 0.05$ was used to determine significant effects.

Results and Discussion

After 58 d, the height (Fig. 1A–D), diameter (Fig. 1E–H), and GI (Fig. 1I–L) were generally suppressed as the DLI increased from 3.2 to 17.1 mol·m^{-2}·d^{-1}, although the magnitude of response to the DLI varied with the cultivar. For example, the height of 'Pom Pom' decreased linearly by 37% (6.7 cm),

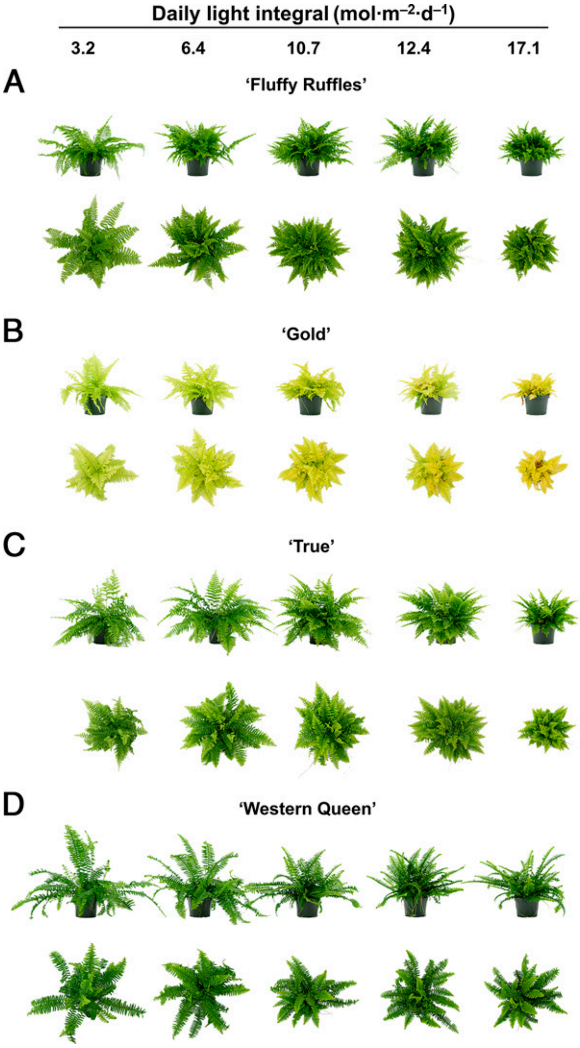

Fig. 2. Depiction of (**A**) 'Fluffy Ruffles', (**B**) 'Gold', and (**C**) 'True' Boston swordfern [*Nephrolepis exaltata* (L.) Schott] and (**D**) 'Western Queen' Australian swordfern [*N. obliterata* (R. Br.) J. Sm.] at 58 d after transplanting. Plants were grown under fixed shadecloth providing ≈86%, 62%, 42%, or 26% shade or no shade (≈0%) from ambient solar light and day-extension and supplemental lighting from high-pressure sodium lamps delivering ≈20, 53, 69, 95, or 138 μmol·m^{-2}·s^{-1} for 16 h (0600–2200 HR), thereby establishing average photosynthetic daily light integrals of 3.2, 6.4, 10.7, 12.4, and 17.1 mol·m^{-2}·d^{-1}.

whereas the height of 'Compacta' only decreased by 20% (4 cm) as the DLI increased from 3.2 to 17.1 mol·m^{-2}·d^{-1} (Fig. 1A and C). The observed relationship of the decreasing plant height with the increasing DLI is consistent with that reported by other studies (Currey and Erwin, 2011; Fausey et al., 2005; Faust et al., 2005; Rezai et al., 2018; Owen, 2017). For example, as the DLI increased from 5 to 20 mol·m^{-2}·d^{-1}, the stem length at the visible bud for lavender (*Lavandula angustifolia* Mill. 'Hidcote Blue'), wand flower (*Gaura lindheimeri* Engelm. and A. Gray 'Siskiyou Pink'), and yarrow (*Achillea ×millefolium* L. 'Red Velvet') decreased by 24% (4.8 cm), 35% (2.4 cm), and 35% (5.4 cm), respectively (Fausey et al., 2005). Faust et al. (2005) reported that an increasing DLI from 5 to 43 mol·m^{-2}·d^{-1} decreased the plant height of ageratum and petunia. Similarly, as the DLI increased from 4.3 to 17.2 mol·m^{-2}·d^{-1}, the plant height of *K. nyikae* decreased by 40% (21 cm) (Currey and Erwin, 2011). In contrast, previous studies observed increased plant height as the DLI increased (Currey and Erwin, 2011; Faust et al., 2005; Garland et al., 2010). For example, Garland et al. (2010) reported that the plant heights of 'Kong Red' and 'Wizard Coral' coleus [*Solenostemon scutellarioides* (L.) Codd] were 25% and 22% taller, respectively, when plants were grown under a DLI of 10 mol·m^{-2}·d^{-1} rather than 2.9 mol·m^{-2}·d^{-1}. Although previous studies demonstrated a plant height response to DLI, in most instances, the maximum plant response to DLI was not identified because the response never reached a plateau (Faust and Logan, 2018). However, in the current study, 'Montana' (Fig. 1B) best fit a QP model in which height suppression plateaued at 12.5 cm with 16.6 mol·m^{-2}·d^{-1}, thereby indicating that increasing the DLI further would not further suppress plant height. Overall, it is apparent that one cannot generalize the specific effect of the DLI on plant height (Faust et al., 2005); however, incorporating more DLI treatments to establish plateau models in future studies is warranted.

The plant diameter decreased linearly as the DLI increased, but only for 10 cultivars. For example, the diameter of 'Fluffy Ruffles' decreased from 46.1 to 29.8 cm (35%) as the DLI increased from 3.2 to 17.1 mol·m^{-2}·d^{-1} (Fig. 1E). The widest crown width of the American alumroot (*Heuchera americana* L. 'Dale's Strain') was significantly smaller at 21.8 mol·m^{-2}·d^{-1} than at 7.5 to 14.9 mol·m^{-2}·d^{-1} (Garland et al., 2012). In contrast, Garland et al. (2010) reported that the widest plant width of 'Kong Red' coleus showed a positive linear correlation with an increasing DLI; plants were 21% wider with a DLI of 10 mol·m^{-2}·d^{-1}rather than 2.9 mol·m^{-2}·d^{-1}. Although previous studies only measured the widest plant width, we quantified the plant diameter to capture the round, mounding growth habit of the swordfern cultivars investigated, which can be translated to an ornamental quality indicator to determine if the plant exhibits a balanced shape for hanging basket or container production. Our results show that plants did exhibit a balanced and compact shape, regardless of the DLI (Fig. 2). Furthermore, in the current study, the plant diameters of 'Compacta' (Fig. 1E) and 'Super' (Fig. 1G) best fit QP models when the diameter suppression plateaued at 34.0 cm with 11 mol·m^{-2}·d^{-1} and at 42.7 cm with 14.7 mol·m^{-2}·d^{-1}, respectively, indicating that increasing the DLI further would not suppress the diameter. Like plant height, the specific effect of the DLI on plant diameter or width may not be generalized.

Growth indices for each cultivar followed a similar trend as plant diameter, although it is not surprising because the GI is an integrated measurement of height and diameter, and most swordfern cultivars investigated have a mounding growth habit. For example, the GI of 'Fluffy Ruffles' decreased linearly by 34% as the DLI increased from 3.2 to 17.2 mol·m^{-2}·d^{-1} (Fig. 1I), resulting in smaller compact plants. Furthermore, the GI for 'Compacta' (Fig. 1I) and 'Super' (Fig. 1K) best fit QP models when overall growth suppression plateaued at 28.2 cm with 11.3 mol·m^{-2}·d^{-1} and at 35.7 cm with 15.5 mol·m^{-2}·d^{-1}, respectively, thereby indicating that increasing the DLI further would not result in overly compact plants.

Increasing the DLI significantly differently affected the frond number of each cultivar (Fig. 1M–P). As the DLI increased from 3.2 to 17.1 mol·m^{-2}·d^{-1}, the frond numbers of 'Compacta', 'Nevada', 'Petticoat', and 'Western Queen' increased linearly by 42% (46 fronds), 29% (34 frond), 37% (27 fronds), and 25% (18 fronds), respectively (Fig. 1M–P). These results are consistent with those of previous reports (Brand, 1997; Garland et al., 2010; 2012; Oh et al., 2009; Pennisi et al., 2005; Rezai et al., 2018; Yeh and Wang, 2000). For example, Oh et al. (2009) reported that the leaf number of cyclamen (*Cyclamen persicum* Mill. 'Metis Scarlet Red') increased as the DLI increased from 1.4 to 17.3 mol·m^{-2}·d^{-1}. Garland et al. (2010) reported that the leaf numbers of 'Kong Red' and 'Wizard Coral' coleus plants increased linearly as the DLI increased from to 2.9 to 10 mol·m^{-2}·d^{-1}. Although four cultivars showed positive linear correlations with the frond number and DLI, almost all remaining cultivars best fit QP models. The number of fronds for 'Blue Bells', 'Fluffy Ruffles', 'Petticoat', 'Pom Pom', 'Super', 'Tiger', and 'True' plateaued at 103, 113, 83, 108, 108, 47, and 123 fronds, respectively, at DLIs of 16.3, 6.6, 10.2, 10.4, 13.0, 5.5, and 10.1 mol·m^{-2}·d^{-1}, respectively, indicating that increasing the DLI further would not result in increased frond

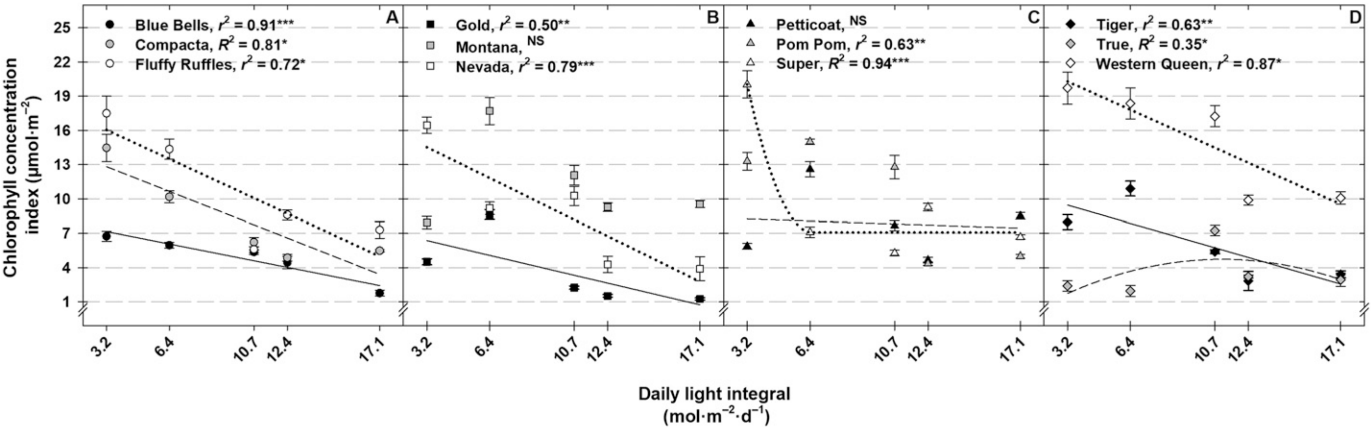

Fig. 3. Linear, quadratic, and nonlinear plateau regression models for the average chlorophyll concentration index of 11 cultivars of Boston swordfern [*Nephrolepis exaltata* (L.) Schott Blue Bells, Compacta, Fluffy Ruffles, Gold, Montana, Nevada, Petticoat, Pom Pom, Super, Tiger, and True] and one cultivar of Australian swordfern [*N. obliterata* (R. Br.) J. Sm. Western Queen] at 58 d after transplant. Plants were grown under fixed shadecloth providing ≈86%, 62%, 42%, or 26% shade or no shade (≈0%) from ambient solar light and day-extension and supplemental lighting from high-pressure sodium lamps delivering ≈20, 53, 69, 95, or 138 μmol·m^{-2}·s^{-1} for 16 h (0600–2200 HR), thereby establishing average photosynthetic daily light integrals of 3.2, 6.4, 10.7, 12.4, and 17.1 mol·m^{-2}·d^{-1}. Each symbol represents a mean of eight samples, and error bars represent ± *SE*. For each model, corresponding r^2 (linear) or R^2 (quadratic and nonlinear plateau) values and significance at $P \leq 0.05$ (*), 0.001 (**), or 0.0001 (***) or no significance (^{NS}) are presented.

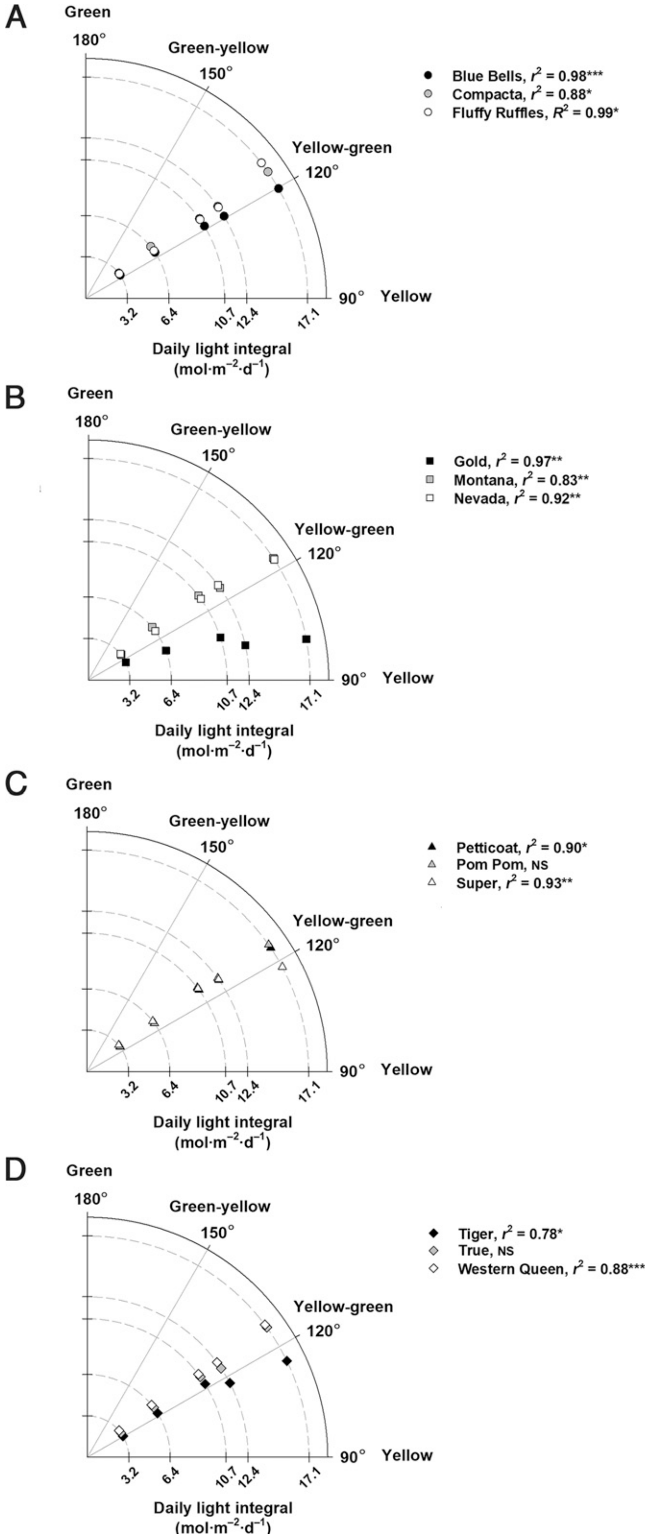

Fig. 4. Polar models for average hue angle of 11 cultivars of Boston swordfern [*Nephrolepis exaltata* (L.) Schott Blue Bells, Compacta, Fluffy Ruffles, Gold, Montana, Nevada, Petticoat, Pom Pom, Super, Tiger, and True] and one cultivar of Australian swordfern [*N. obliterata* (R. Br.) J. Sm. Western Queen] at 58 d after transplant. Plants were grown under fixed shadecloth providing ≈86%, 62%, 42%, or 26% shade or no shade (≈0%) from ambient solar light and day-extension and supplemental lighting from high-pressure sodium lamps delivering ≈20, 53, 69, 95, or 138 μmol·m^{-2}·s^{-1} for 16 h (0600–2200 HR), thereby establishing average photosynthetic daily light integrals of 3.2, 6.4, 10.7, 12.4, and 17.1 mol·m^{-2}·d^{-1}. Each symbol represents a mean of eight samples. For each model, corresponding r^2 (linear) or R^2 (quadratic) values and significance at $P \leq 0.05$ (*), 0.001 (**), or 0.0001 (***) or no significance (^{NS}) are presented.

numbers. Additionally, visual observations for frond size varied by cultivar, and fronds were often smaller among plants under shade structures with higher light intensities than lower light intensities. To support our observations, one recently mature frond per plant was sampled from each cultivar to generate FLA survey data. Interestingly, preliminary statistical analyses of the sample population found that ‘Blue Bells’ was unaffected by DLI, whereas the FLA of ‘Compacta’, ‘Gold’, and ‘Western Queen’ decreased linearly by 46% (26.7 cm^2), 62% (47 cm^2), and 52% (51 cm^2), respectively, as the DLI increased from 3.2 to 17.1 mol·m^{-2}·d^{-1}. Data for all other cultivars are not reported herein, but further investigations of the FLA for all fronds regardless of age are needed to accurately assess the FLA response to increasing DLI. Furthermore, our visual observations and FLA survey data are consistent with those of Rezai et al. (2018), who reported that the leaf area decreased by 71% as the shade level decreased from 70% to 0% when sage (*Salvia officinalis* L.) plants were grown under ambient daylight in mini-tunnels.

Biomass accumulation increased with the DLI for all cultivars, although the magnitude of the response to the DLI varied by cultivar (Fig. 1Q–T). Nine cultivars best fit a QP model. Plant dry mass for ‘Blue Bells’, ‘Compacta’, ‘Fluffy Ruffles’, ‘Montana’, ‘Nevada’, ‘Petticoat’, ‘Super’, ‘True’, and ‘Western Queen’ plateaued at 10.1, 10.2, 11.6, 8.4, 15.1, 10.6, 15.2, 14.8, and 19.0 g, respectively, at DLIs of 10.0, 13.0, 7.5, 15.5, 9.4, 15.2, 10.3, 10.9, and 16.5 mol·m^{-2}·d^{-1}, respectively, indicating that increasing the DLI further would not result in increased biomass accumulation. The PDM increased at a quadratic rate for ‘Gold’, ‘Pom Pom’, and ‘Tiger’ as the DLI increased (Fig. 1R–T). Our results agree with those of previous reports of the effect of DLI on biomass accumulation for several floriculture crops (Currey and Erwin, 2011; Fausey et al., 2005; Faust et al., 2005; Garland et al., 2010; Oh et al., 2009; Owen, 2017; Warner and Erwin, 2003). For instance, Faust et al. (2005) reported that the PDM of ageratum, begonia, impatiens, marigold, petunia, salvia, and zinnia increased as the DLI increased from 5 to 43 mol·m^{-2}·d^{-1}. Similarly, the PDM of ‘Kong Red’ and ‘Wizard Coral’ coleus plants increased by 316% (5.9 g) and 306% (4.9 g) as the DLI increased from 2.9 to 10 mol·m^{-2}·d^{-1} (Garland et al., 2010). However, in the current study, we determined the DLI at which the PDM was optimized or saturated. A similar instance was reported for ‘Metis Scarlet Red’ cyclamen; the dry mass of 16-week-old plants increased as the DLI increased from 1.4 to ≈11.5 mol·m^{-2}·d^{-1}, but increasing the DLI to 17.3 mol·m^{-2}·d^{-1} did not increase the dry mass (Oh et al., 2009).

The intensity and distribution of chlorophylls are known to contribute to leaf color (Gazula et al., 2007) and, thus, aesthetic appeal and ornamental value. Environmental factors such as DLI (light quantity and duration) can strongly influence the accumulation of chlorophyll pigments (Owen and Lopez, 2015). Nondestructive instrumental measurements can determine the chlorophyll content and foliage color (Owen and Lopez, 2015, 2017). For instance, Wang et al. (2005) demonstrated that a soil–plant analysis development (SPAD) meter could be used as a nondestructive instrumental quality assessment of 10 ornamental green-leaved foliage plants. However, Owen and Lopez (2015, 2017) used a tristimulus colorimeter to measure the foliage color of four lettuce (*Lactuca sativa* L. Cherokee, Magenta, Ruby Sky and Vulcan) cultivars, Black Velvet geranium, and purple fountain grass [*Pennisetum* ×*advena* Wipff and Veldkamp (formerly known as *P. setaceum* Forsk. Chiov. Rubrum)] grown under different end-of-production light qualities and intensities. Although SPAD meters are acceptable for estimating leaf greenness, previous research demonstrated that CCI meters have a higher accuracy when determining the nondestructive chlorophyll concentration based on CCI measurements (Parry et al., 2014). Therefore, we used a CCI meter in the current study. The CCI for each cultivar was influenced by increasing the DLI, although to different magnitudes (Fig. 3A–D). Chlorophyll concentration indices for 'Montana' and 'Petticoat' were unaffected by increasing the DLI, whereas decreasing linear responses were observed for eight cultivars. For example, as the DLI increased from 3.2 to 17.1 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, the CCI of 'Fluffy Ruffles' decreased linearly from 11.2 to 5.6 $\mu\text{mol}\cdot\text{m}^{-2}$ (50%) (Fig. 3A). An increasing quadratic response was observed for 'True', whereas the CCI of 'Super' best fit a QP in which the CCI plateaued at 7.1 $\mu\text{mol}\cdot\text{m}^{-2}$ with 6.1 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. As expected, the CCI decreased when the DLI increased from 3.2 to 17.1 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$.

Lightness and C* were unaffected by the increasing DLI (data not shown). Our results are inconsistent with those reported by Kim et al. (2012), who found that increasing DLIs of ≈0.2, 0.4, 0.8, 3.9, and 7.8 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ provided by triband phosphor fluorescent lamps decreased the C* of English ivy (*Hedera helix* L. 'Golden Ingot'). The hue angle decreased with the DLI, although the responses varied by cultivar (Fig. 4E–H). The hue angle of 'Pom Pom' and 'True' were unaffected, whereas the *h*° of nine cultivars decreased linearly and that of 'Fluffy Ruffles' decreased quadratically with the increasing DLI (Fig. 4A–D). For instance, as the DLI increased from 3.2 to 17.1 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, the pinnule *h*° of 'Gold' and 'Super' decreased linearly from 115° to 101° (13%) and from 130° to 118° (9%), respectively; therefore, the foliage exhibited yellow to yellow–green hues. Visually, we could not differentiate plants that were determined to have yellow to yellow–green hues. We did observe necrotic spotting and some bleaching among pinnules and fronds of 'Gold' when plants were grown under a DLI of 17.1 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$; therefore, we concluded that these plants would be commercially unsatisfactory (Fig. 2B). Faust et al. (2005) reported similar DLI effects resulting in reduced ornamental plant quality of begonia and impatiens.

Conclusion

This study demonstrates the effects of DLI on growth, morphology, physiology, and, thus, overall quality and aesthetic value of 12 *Nephrolepis* cultivars. When the results of this study are considered together, growers should maintain ≈10 to 12 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ during greenhouse Boston and Australian swordfern production; however, DLIs ≥5.5 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ and ≤16.5 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ were shown to improve the quality of some swordfern cultivars. Therefore, greenhouse growers can deploy supplemental and/or day-extension lighting to increase the DLI during the months of late fall to early spring, when ambient outdoor DLI is low, to improve the plant quality of Boston and Australian swordfern. Collectively, these results expand the DLI requirements, plant growth effects, and placement of Boston and Australian swordferns in greenhouses when grown in hanging baskets under single or multilayer systems. This work will further benefit greenhouse growers by providing more precise DLI recommendations for the Boston and Australian swordfern cultivars investigated.

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