HortScience 43(7):2052–2059. 2008.

Photosynthetic Daily Light Integral during Propagation Influences Rooting and Growth of Cuttings and Subsequent Development of New Guinea Impatiens and Petunia

Roberto G. Lopez[1,2] and Erik S. Runkle
Department of Horticulture, Michigan State University, East Lansing, MI 48824

Additional index words. biomass accumulation, flowering, *Impatiens hawkeri*, light intensity, *Petunia ×hybrida*

Abstract. **A majority of commercial propagation of herbaceous ornamental cuttings occurs during the winter when the photosynthetic daily light integral (DLI) is relatively low. We quantified how the mean DLI influenced rooting and subsequent growth and development of two popular vegetatively propagated species, New Guinea impatiens (*Impatiens hawkeri* Bull.) and petunia (*Petunia ×hybrida* hort. Vilm.-Andr.). Three cultivars of each species were propagated under a mean DLI ranging from 1.2 to 10.7 mol·m^{-2}·d^{-1}. Cuttings were rooted in a controlled greenhouse environment maintained at 24 to 25 °C with overhead mist, a vapor-pressure deficit of 0.3 kPa, and a 12-h photoperiod. Rooting and growth evaluations of cuttings were made after 8 to 16 d. In a separate experiment, rooted cuttings under DLI treatments were then transplanted into 10-cm containers and grown in a common greenhouse at 21 ± 2 °C under a 16-h photoperiod to identify any residual effects on subsequent growth and development. In both species, rooting, biomass accumulation, and quality of cuttings increased and subsequent time to flower generally decreased as mean propagation DLI increased. For example, root number of petunia 'Tiny Tunia Violet Ice' after 16 days of propagation increased from 17 to 40 as the propagation DLI increased from 1.2 to 7.5 mol·m^{-2}·d^{-1}. In addition, cutting shoot height decreased from 6.3 to 4.5 cm, and root and shoot dry biomass of cuttings harvested after 16 days of propagation increased by 737% and 106%, respectively. Subsequent time to flower for 'Tiny Tunia Violet Ice' from the beginning of propagation decreased from 50 to 29 days as propagation DLI increased from 1.4 to 10.7 mol·m^{-2}·d^{-1} regardless of the DLI provided after propagation. In New Guinea impatiens 'Harmony White', root and shoot dry weight of cuttings increased by 1038% and 82%, respectively, and subsequent time to flower decreased from 85 to 70 days as the propagation DLI increased from 1.2 to 10.7 mol·m^{-2}·d^{-1}. These experiments quantify the role of the photosynthetic DLI during propagation on the rooting and subsequent growth and development of vegetatively propagated herbaceous ornamental cuttings.**

Annual bedding plants are the largest (45%) segment of the U.S. commercial floriculture industry with a reported wholesale value of $1.76 billion in 2007 (U.S. Department of Agriculture, 2008). In the past decade, annual and perennial crops have increasingly been propagated by shoot-tip cuttings; in 2006, U.S. greenhouse growers imported 878 million nonrooted cuttings of annuals and perennials with a reported wholesale value of U.S. $61 million (U.S. Department of Agriculture, 2007). In the United States, cuttings of bedding plants are typically received from offshore production facilities and propagated in greenhouses from December to March for sales to consumers in spring and early summer. During propagation, the integrated photosynthetic photon flux (*PPF*) [daily light integral (DLI)] outdoors can range from 5 to 20 mol·m^{-2}·d^{-1} across the northern half of the United States (Korczynski et al., 2002). In greenhouses, light levels can be 50% or less of that outdoors because of structures, glazing, shading, and obstructions (Hanan, 1998). Therefore, the DLI during propagation can be as low as 1 to 5 mol·m^{-2}·d^{-1} and even lower during extended periods of cloudy weather.

Vegetative cuttings require a minimum quantity of photosynthetic light to provide a supply of carbohydrates for callus and adventitious root initiation and development (Haissig, 1986; Veierskov, 1988). Light intensities below this minimum can delay root growth and development, leading to an extended rooting period and increased probability of rooting failure. Adventitious root formation and growth were influenced by the *PPF* and photosynthesis during propagation of pea (*Pisum sativum* L.) (Davis and Potter, 1981), geranium (*Pelargonium ×hortorum* L.H. Bail.) (Rapaka et al., 2005) and rose (*Rosa ×hybrida* L.) cuttings (Costa and Challa, 2002). However, rooting of geranium was also positively correlated with the preharvest leaf sucrose concentration when propagation *PPF* was low (Druege et al., 2004) such as less than 100 µmol·m^{-2}·s^{-1} (Rapaka et al., 2005). Conversely, stomatal closure, reduced turgor, and lower osmotic potential (ψ_S) from excessive light can inhibit root formation because of water and temperature stress and photoinhibition (Eliasson and Brunes, 1980; Enfield, 2002; Grange and Loach, 1985).

Numerous studies have been performed to understand the effects of DLI or light intensity on propagation of seedlings, cuttings, or microshoots. These studies have species-specific results and primarily focused on either shoot growth (e.g., stem elongation and shoot biomass) or rhizosphere growth (e.g., rooting percentage, root number, and biomass) and subsequent flowering in herbaceous and woody species. In herbaceous cuttings and seedlings such as celosia (*Celosia argentea* L.), seed impatiens (*Impatiens wallerana* Hook. f.), salvia (*Salvia splendens* Sell ex Roem. & Schult.), marigold (*Tagetes patula* L.), pansy (*Viola ×wittrockiana* Gams.) (Pramuk and Runkle, 2005a), baby's breath (*Gypsophila paniculata* L.) (Islam and Willumsen, 2001), petunia (Cabaleiro and Economou, 1992), and phlox (*Phlox paniculata* L.) (Enfield, 2002), rooting and shoot biomass and quality generally increased with increasing DLI or light intensity. For example, rooting percentage and dry weight of baby's breath cuttings were greater after 3 weeks in a propagation greenhouse when plants were provided with a DLI of 12 mol·m^{-2}·d^{-1} compared with 7 mol·m^{-2}·d^{-1} (Islam and Willumsen, 2001). In addition, cuttings propagated under a DLI of 12 mol·m^{-2}·d^{-1} subsequently flowered 14 d earlier than cuttings propagated under a DLI of 7 mol·m^{-2}·d^{-1}.

To our knowledge, no studies have been published on the effects of DLI after 8 to 16 d of propagation on shoot and root biomass accumulation and the effects on subsequent development of vegetatively propagated bedding crops. Petunia (*Petunia ×hybrida* hort. Vilm.-Andr.) and New Guinea impatiens (*Impatiens hawkeri* Bull.) are two of the most valuable annual bedding crops commonly propagated from cuttings (U.S. Department

Received for publication 30 June 2008. Accepted for publication 4 Aug. 2008.
Based on part of a dissertation in partial fulfillment of the requirements for the Ph.D. degree at Michigan State University.
We gratefully acknowledge funding from the Floriculture Industry Research and Scholarship Trust, the American Floral Endowment, growers providing support for Michigan State University floriculture research, and support from the Michigan Agricultural Experiment Station.
[1]Assistant Professor, Horticulture and Extension Specialist. Current address: Department of Horticulture and Landscape Architecture, Purdue University, 625 Agriculture Mall Drive, West Lafayette, IN 47907.
[2]To whom reprint requests should be addressed; e-mail rglopez@purdue.edu

of Agriculture, 2008). The objective of this study was to quantify the effects of DLI during propagation on rooting, growth, and quality (cutting height and biomass accumulation) of each species during the rooting stage and to determine whether there were any residual effects of DLI on subsequent growth and development after transplant. In addition, three cultivars of each species were chosen to determine the responses to DLI within a species.

Materials and Methods

Plant material and culture. Petunia and New Guinea impatiens stock plants were grown in 15-cm (1.3-L) and 16-cm (2.4-L) round containers (Dillen Products, Middlefield, OH), respectively, filled with a mix containing 70% peatmoss, 21% perlite, and 9% vermiculite (Sure-Mix; Michigan Grower Products, Galesburg, MI). Plants were irrigated as necessary with reverse-osmosis water supplemented with water-soluble fertilizer to provide the following ($mg \cdot L^{-1}$): 125 N–12 P–100 K–65 Ca, 1.0 Fe and Cu, 0.5 Mn and Zn, 0.3 B, and 0.1 Mo (MSU Special; Greencare Fertilizers, Chicago, IL).

Petunia 'Tiny Tunia Violet Ice', 'Double Wave Spreading Rose', and 'Supertunia Mini Purple' stock plants were grown in glass greenhouses in East Lansing, MI (lat. 43° N) at a mean temperature of 20.7 ± 1.7 °C and a mean DLI of 11.3 $mol \cdot m^{-2} \cdot d^{-1}$. Plants were grown under a 12-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 extended with day-extension lighting (≈2 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at canopy level) with incandescent lamps from 1700 to 2000 HR. From 0800 to 1700 HR, high-pressure sodium (HPS) lamps provided a supplemental *PPF* of 50 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at plant height [as measured with a light quantum sensor containing 10 photodiodes (Apogee Instruments, Inc., Logan, UT)] when the ambient greenhouse *PPF* was less than 140 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Temperature on each bench was measured by an aspirated and enclosed thermocouple every 10 s, and hourly averages were recorded by a CR-10 data logger (Campbell Scientific, Logan, UT). The data logger controlled a 1500-W electric heater under each bench, which provided supplemental heat as needed to provide uniform night temperatures of 20 °C. Ethephon (Florel; Rhône-Poulenc Ag Company, Research Triangle Park, NC) with a surfactant (Capsil; Aquatrols, Paulsboro, NJ) was applied as a foliar spray at a concentration of 150 to 200 $mg \cdot L^{-1}$ and a volume of 0.2 $L \cdot m^{-2}$ every 4 weeks to abort flower buds.

New Guinea impatiens 'Harmony White', 'Harmony Magenta', and 'Celebrette Red' stock plants were maintained under a 16-h photoperiod at a mean temperature of 23.9 ± 2.4 °C and a mean DLI of 9.5 $mol \cdot m^{-2} \cdot d^{-1}$. The photoperiod was a constant 16 h (0600 to 2200 HR) consisting of natural daylengths with day-extension lighting from HPS lamps that delivered a supplemental *PPF* of 50 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at plant height. Ethephon was applied to New Guinea impatiens as described previously but at a concentration of 500 or 750 $mg \cdot L^{-1}$ every 2 weeks to abort flower buds.

Cutting harvest. Approximately 150 uniform 3-cm vegetative petunia terminal stem cuttings were harvested from stock plants on 1 Aug. 2004, 25 Oct. 2004, and 7 Sept. 2005 (Expt. 1) and 16 Aug. and 1 Nov. 2005 (Expt. 2); and ≈150 uniform 4-cm vegetative New Guinea impatiens terminal stem cuttings were harvested from stock plants on 22 Aug. 2004, 20 Sept. 2004, and 16 Aug. 2005 (Expt. 1) and 2 Feb. and 16 Aug. 2005 (Expt. 2). Cuttings were harvested beginning at 1000 HR and were stuck in 72-cell (28-mL) plug trays (Landmark Plastic Corp., Akron, OH) in a 50% commercial peat-based mix (Sure-Mix) and 50% screened coarse perlite (Therm-O-Rock East, Inc., New Eagle, PA) mix.

Propagation environment. All cuttings were rooted in a glass greenhouse under a 12-h photoperiod with an air temperature set point of 24 °C. Air temperature was measured as previously described, and media temperature was measured by 36-gauge type E thermocouples (TT-E-36; Omega Engineering Inc., Stamford, CT) placed 2 cm below the media surface. Mean temperatures are provided in Tables 1 and 2. The 12-h photoperiod consisted of a 9-h truncated natural day (as described previously) extended with light from soft-white fluorescent lamps (BIAX FLE15TBX/L/SPX27; General Electric, Fairfield, CT) (≈3 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at canopy level) from 1700 to 2000 HR. Overhead mist containing reverse-osmosis water supplemented with water-soluble fertilizer was provided as necessary and delivered the following ($mg \cdot L^{-1}$): 50 N–8 P–42 K–22 Ca, 1.0 Fe and Cu, 0.5 Mn and Zn, 0.3 B, and 0.1 Mo (MSU Special). Misting was controlled by an environmental computer as a function of time and accumulated *PPF*. A line quantum sensor (Apogee Instruments, Inc.) positioned in the center of the propagation house recorded light intensity every 10 s. Five seconds of misting were provided when the integrated light intensity reached 0.20 $mol \cdot m^{-2} \cdot h^{-1}$ or after 60 min, whichever occurred first. A vapor-pressure deficit of 0.3 kPa was maintained by the injection of steam or fine mist (Humidifan Turbo XE; Jaybird Manufacturing, State College, PA).

DLI treatments were created in the propagation environment using no shadecloth or fixed woven shadecloths placed above individual propagation compartments that reduced light by ≈30%, 55%, or 70% (OLS 30, 50, and 70; Ludvig Svensson, Charlotte, NC). Line quantum sensors (as described previously) were placed directly above cuttings in the four light compartments to measure the *PPF*. Thermocouples and line quantum sensors were connected to a CR10 data logger, and data were recorded every 10 s. The mean DLI was calculated for each environment and replication (Table 1).

Effects of propagation daily light integral on rooting (Expt. 1). Ten cuttings per DLI treatment were harvested 8, 12, and 16 d (petunia) or 10, 13, and 16 d (New Guinea impatiens) after the start of propagation for each cultivar. For clarity, only 8 and 16 d and 10 and 16 d data are presented for petunia and New Guinea impatiens, respectively. The rooting medium was carefully washed off and roots and shoots were separated and dry weights were recorded after drying in an oven at 70 °C for 1 week for replications 1, 2, and 3. The root-to-shoot dry weight ratio was also determined. The number of roots, length of the longest root, and height of the shoot from the medium level were recorded for each cutting for replications 2 and 3.

Effects of propagation daily light integral on subsequent flowering (Expt. 2). Sixteen days after the start of propagation, 10 petunia and New Guinea impatiens cuttings of each cultivar from each DLI treatment were transplanted into 10-cm square pots containing a peat-based media (Suremix). The plants were grown at 20 °C under a 16-h photoperiod (as described previously), and chlorophyll

Table 1. Mean media and air temperatures during 16 d of propagation and mean daily light integral (DLI) of petunia and New Guinea impatiens cuttings propagated under four DLI treatments after 8, 12, and 16 d and 10, 13, and 16 d, respectively (Expt. 1).

Species and propagation dates	Temperature (°C)		DLI ($mol \cdot m^{-2} \cdot d^{-1}$)											
			Shade				Shade				Shade			
	Media	Air	70%	55%	30%	None	70%	55%	30%	None	70%	55%	30%	None
Petunia			8 d				12 d				16 d			
Aug. 2004	24.0 ± 1.3	24.5 ± 1.5	1.8	3.2	6.3	9.5	1.6	2.7	5.4	8.5	1.6	2.8	5.4	8.4
Oct. 2004	24.4 ± 1.3	25.4 ± 1.3	1.2	1.9	3.4	4.3	1.1	1.7	2.9	3.6	1.2	1.9	3.4	3.9
Sept. 2005	22.4 ± 1.6	24.5 ± 1.5	3.4	4.7	7.0	8.8	3.2	4.3	6.4	8.1	3.0	4.0	5.9	7.5
New Guinea impatiens			10 d				13 d				16 d			
Aug. 2004	24.1 ± 1.3	24.7 ± 1.6	1.2	2.0	3.7	5.9	1.3	2.1	3.7	5.9	1.3	2.1	3.7	5.9
Sept. 2004	22.5 ± 1.4	24.1 ± 1.7	2.1	3.4	4.1	6.2	2.0	3.5	4.2	6.4	1.9	3.5	4.2	6.3
Aug. 2005	22.6 ± 1.1	24.4 ± 1.9	3.8	4.5	6.1	10.4	4.0	4.7	6.3	10.8	4.1	4.6	6.1	10.7

Table 2. Mean media and air temperatures, vapor-pressure deficit (VPD), and daily light integral (DLI) during 16 d of propagation under four DLI treatments and average air temperature and DLI during subsequent forcing of petunia and New Guinea impatiens (Expt. 2).

	Propagation							Forcing	
	Temperature (°C)		VPD	DLI ($mol·m^{-2}·d^{-1}$) Shade				Temperature	DLI
Propagation dates	Media	Air	(kPa)	70%	55%	30%	None	(°C)	($mol·m^{-2}·d^{-1}$)
				Petunia					
Aug. 2005	23.5 ± 3.4	24.4 ± 1.1	0.44	4.1	4.6	6.1	10.7	21.3 ± 1.9	13.0
Nov. 2005	22.9 ± 1.5	24.1 ± 0.9	0.39	1.4	2.0	3.0	4.7	19.9 ± 0.9	7.4
				New Guinea impatiens					
Feb. 2005	22.3 ± 1.7	25.3 ± 1.0	0.38	1.6	2.2	3.4	4.3	20.5 ± 1.2	15.7
Aug. 2005	23.5 ± 3.4	24.4 ± 1.1	0.44	4.1	4.6	6.1	10.7	21.9 ± 1.9	13.0

fluorescence (F_v/F_m) of a fully expanded leaf was measured 24 h after transplant, beginning at 1300 HR, with a portable chlorophyll fluorescence system (Plant Efficiency Analyzer; Hansatech Instruments Ltd., Norfolk, U.K.) to determine if photoinhibition had occurred. Leaves were dark-acclimated for 15 min with the manufacturer's plastic and foam clips before measurements were recorded. Mean temperature and DLI from transplant until flowering are provided in Table 2. Time to flower from the beginning of propagation, number of flower buds, number of lateral branches, and plant height from the media level to the tip of the longest shoot were recorded on the date the first flower opened on each plant, and shoot dry weight was determined as described previously.

Data analysis. Cuttings were randomly assigned to each DLI treatment and DLI treatments were randomized between propagation dates within the greenhouse. Data were analyzed using the SAS (SAS Institute, Cary, NC) mixed model procedure (PROC MIXED) for analysis of variance. Regression analysis was performed using Sigma Plot 8.0 (Systat Software, Inc., San Jose, CA). For New Guinea impatiens, the highest DLI treatment was not included in the regression analysis because it appeared to be superoptimal.

Results

Petunia. Root number after 8 and 16 d of propagation increased as DLI increased from 1.2 to 9.5 $mol·m^{-2}·d^{-1}$ in all three cultivars (Figs. 1A, F, and K). In petunia 'Tiny Tunia Violet Ice', 'Double Wave Spreading Rose', and 'Supertunia Mini Purple', average root and shoot dry weight accumulation during the 16 d of propagation increased linearly by 680% and 506%, 2395% and 106%, 108%, and 147%, respectively, as DLI increased from 1.2 to 8.4 $mol·m^{-2}·d^{-1}$ (Figs. 1B, C, G, H, L, and M). DLI did not influence root length of any petunia cultivar (data not presented). Shoot height increased from 4.5 to 6.3, 4.7 to 6.3, and 4.7 to 7.3 cm as DLI decreased from 5.9 to 1.2 $mol·m^{-2}·d^{-1}$ in petunia 'Tiny Tunia Violet Ice', 'Double Wave Spreading Rose', and 'Supertunia Mini Purple', respectively, during the 16 d of propagation (Figs. 1D, I, and N). As propagation DLI increased to 8.4 $mol·m^{-2}·d^{-1}$, the root-to-shoot ratio of cuttings increased from 0.09 to 0.24 in all three cultivars when quantified 16 d after cuttings were propagated (Figs. 1E, J, and O).

Time to flower from the beginning of propagation decreased by 21 and 22 d as the mean DLI during propagation increased from 1.4 to 10.7 $mol·m^{-2}·d^{-1}$ for petunia 'Tiny Tunia Violet Ice' and 'Supertunia Mini Purple', respectively (Figs. 2A and G). For petunia 'Tiny Tunia Violet Ice' and 'Supertunia Mini Purple', the relationship between flower bud number or shoot dry weight accumulation and DLI at first flowering was linear (decreased by 58% and 63%) and quadratic (decreased by 82% and 58%), respectively, as DLI increased from 1.4 to 10.7 $mol·m^{-2}·d^{-1}$ (Figs. 2B, C, H, and I). Time to flower, flower bud number, and shoot dry weight at first flowering of petunia 'Double Wave Spreading Rose' were not influenced by the DLI during propagation (Figs. 2D, E, and F). Chlorophyll fluorescence, lateral branch development, and plant height were not influenced by DLI in any petunia cultivar (data not presented).

New Guinea impatiens. As the mean DLI increased from 1.3 to 6.1 $mol·m^{-2}·d^{-1}$ during the 16 d of propagation, root number increased linearly by 200%, 108%, and 72% in New Guinea impatiens 'Harmony White', 'Harmony Magenta', and 'Celebrette Red', respectively (Figs. 3A, F, and K). Root dry weight increased linearly from 4.9 to 47.4 mg (867%) in 'Harmony White', 2.7 to 19.0 mg (604%) in 'Harmony Magenta', and 4.9 to 33.3 mg (580%) in 'Celebrette Red' (Figs. 3B, G, and L). DLI had little effect on the length of the longest root after 10 d in propagation, but root length in all cultivars increased linearly as DLI increased when measured after the 16 d of propagation (Figs. 3C, H, and M).

Shoot dry weight when measured after the first 10 d of propagation increased at a quadratic rate in 'Harmony White' and 'Celebrette Red'. As DLI increased from 1.3 to 6.1 $mol·m^{-2}·d^{-1}$, shoot dry weight increased linearly by 53%, 32%, and 40% after 16 d of propagation in 'Harmony White', 'Harmony Magenta', and 'Celebrette Red', respectively (Figs. 3D, I, and N). DLI did not significantly influence shoot height of any New Guinea impatiens cultivar (data not presented). After 16 d of propagation, the root-to-shoot ratio of cuttings increased linearly as DLI increased from 1.3 to 6.1 $mol·m^{-2}·d^{-1}$ in all three cultivars (Figs. 3E, J, and O).

Subsequent time to flower was hastened by 15, 14, and 19 d in 'Harmony White', 'Harmony Magenta', and 'Celebrette Red', respectively, as the DLI during propagation increased from 1.6 to 10.7 $mol·m^{-2}·d^{-1}$ (Figs. 4A, D, and G). Shoot dry weight at flowering decreased from 8.5 to 7.2 g in 'Harmony White', 8.7 to 7.1 g in 'Harmony Magenta', and 11.4 to 8.2 g in 'Celebrette Red' (Figs. 4B, E, and H) as DLI during propagation increased. The number of lateral branches at first flowering decreased as DLI increased during propagation in all cultivars (Figs. 4C, F, and I). Chlorophyll fluorescence, flower bud number, and plant height were not influenced by DLI in any cultivar (data not presented).

Discussion

Successful and economically viable propagation of high-quality vegetative transplants requires rapid and uniform rooting. The transplants must be compact, well-branched, fully rooted, and have a large biomass to ensure survival during shipping and the transition to the finish-production environment (Dole and Hamrick, 2006). For the petunia and New Guinea impatiens cultivars tested, root and shoot biomass, the root-to-shoot ratio, and the quality (shoot height) of rooted cuttings increased as DLI increased during propagation until ≈8 $mol·m^{-2}·d^{-1}$. For example, as the mean DLI during 16 d of propagation increased from 1.2 to 8.4 $mol·m^{-2}·d^{-1}$ for petunia and 1.3 to 6.1 $mol·m^{-2}·d^{-1}$ for New Guinea impatiens, average root dry weight and shoot dry weight increased linearly in all cultivars. These results are consistent with findings by Pramuk and Runkle (2005a), who reported that an increasing DLI (from 4.1 to 14.2 $mol·m^{-2}·d^{-1}$) during the seedling stage of celosia, seed impatiens, marigold, and pansy increased shoot dry weight per internode by 64%, 47%, 64%, and 68%, respectively. In addition, seedling height decreased with increasing DLI in celosia, seed impatiens, and salvia.

During the early stages of rooting (8 and 10 d for petunia and New Guinea impatiens, respectively), the influence of increasing DLI on cutting quality was less profound than at later stages. For example, root and shoot biomass accumulation and length of the longest root increased at a quadratic rate when initially

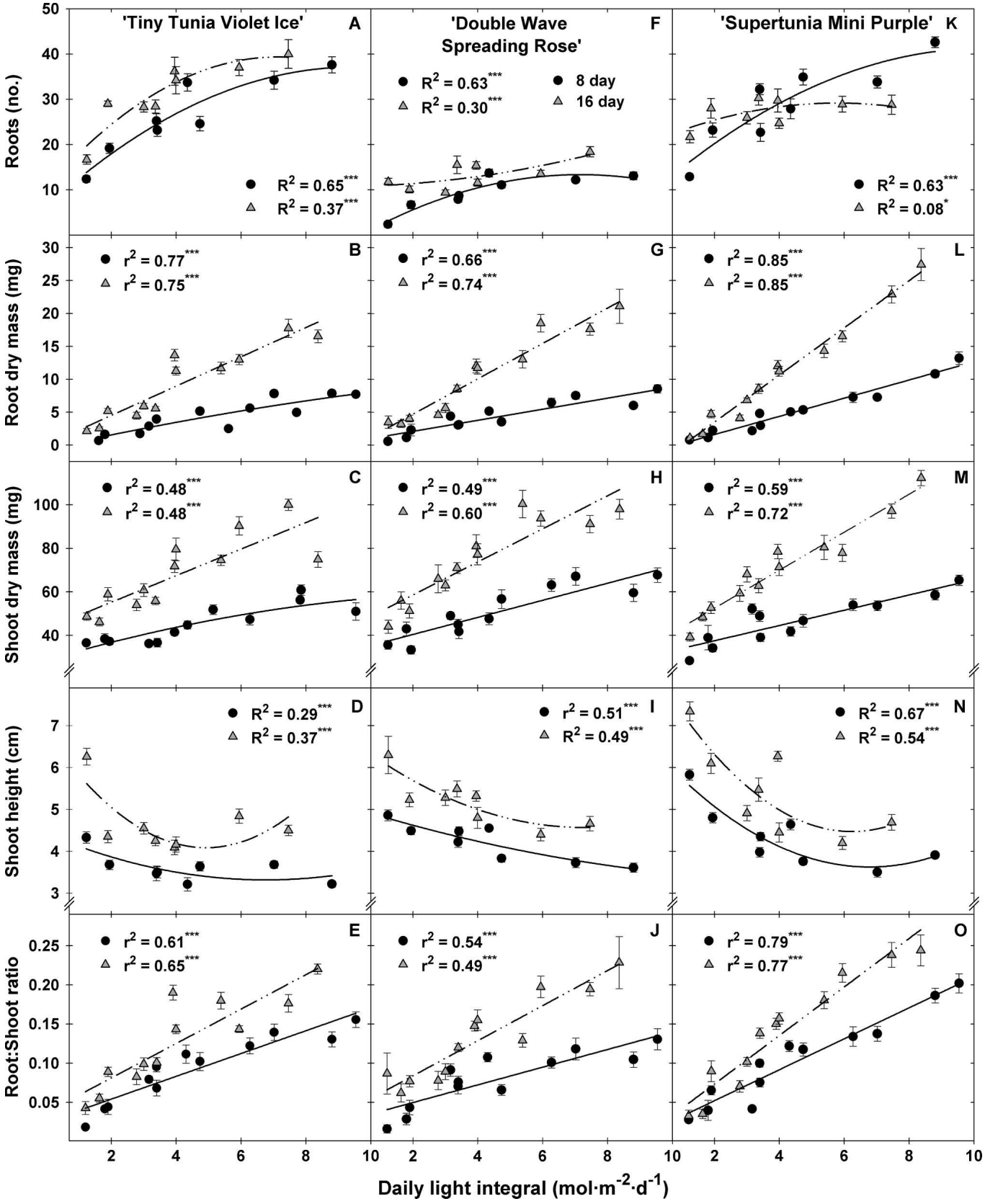

Fig. 1. (**A–O**) Relationships between mean daily light integral and number of roots formed, root dry weight, shoot dry weight, shoot height, and root-to-shoot ratio measured after 8 d (shaded circles) and 16 d (open triangles) of propagation for petunia 'Tiny Tunia Violet Ice', 'Double Wave Spreading Rose', and 'Supertunia Mini Purple' cuttings. 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. Legend in F applies to all figures. $^{*,\ ***}$Significant at $P \leq 0.05$ or 0.001, respectively.

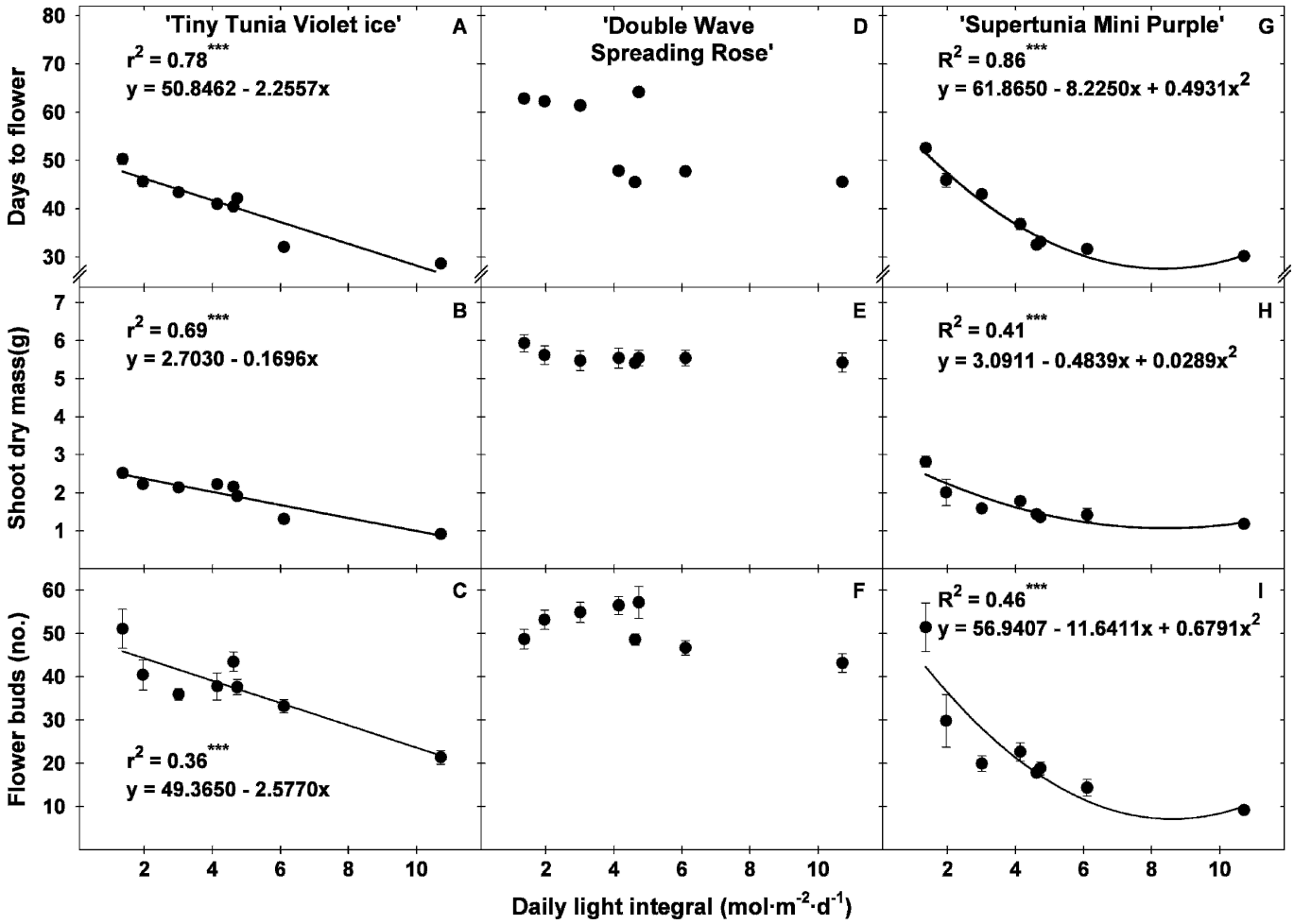

Fig. 2. (**A–I**) Relationships between mean daily light integral during propagation and days to flower from the beginning of propagation, shoot dry weight, and number of flower buds at first flowering for petunia 'Tiny Tunia Violet Ice', 'Double Wave Spreading Rose', and 'Supertunia Mini Purple' cuttings. Each symbol represents the mean of 12 plants, and error bars represent SES of the mean. Equations for regression lines are presented for significant correlations only with corresponding r^2 and R^2. ***Significant at $P \leq 0.001$.

measured and then linearly after 16 d (Figs. 1 and 3). Studies with woody cuttings have also shown that increased DLI has more of an effect on rooting once roots have initiated. Grange and Loach (1985) suggested that during the early propagation stages of woody cuttings of *Hibiscus syriacus* L., *Viburnum* ×*bodnantense* Stearn, and *Weigela florida* (Bunge) A. DC., the DLI be maintained between 2.5 and 3.3 mol·m^{-2}·d^{-1} to avoid reduced rooting primarily as a result of loss of water and ψ_S, turgor pressure, or both. After root initiation, the DLI should be increased because subsequent root growth requires higher irradiances (Grange and Loach, 1985).

However, in certain woody species, increased light intensities during propagation inhibit or reduce rooting. For example, in Japanese maple (*Acer palmatum* Thunb.), the percentage of cuttings that formed adventitious roots under maximum light intensities of 300 and 900 µmol·m^{-2}·s^{-1} was 82% and 64%, respectively, after 4 weeks (Behrens, 1988). Similarly, increased light levels during propagation of hibiscus [*Hibiscus rosa-sinensis* L. and *H. schizopetalus* (Masters) Hook. f.] decreased root number, dry weight, and rooting percentage (Kachecheba, 1976).

Dole and Hamrick (2006) recommend a light intensity of 100 to 200 µmol·m^{-2}·s^{-1} for most vegetatively propagated herbaceous cuttings during the first stage of rooting (propagation to callus formation), which accumulates to a DLI of ≈4 mol·m^{-2}·d^{-1} under a 12-h photoperiod. During the second stage of rooting (after root initiation), the recommended light intensity is 200 to 400 µmol·m^{-2}·s^{-1} (DLI of ≈8 mol·m^{-2}·d^{-1} under a 12-h photoperiod). In a previous study, we determined that the photosynthetic light compensation point (LCP) and saturation range of petunia 'Tiny Tunia Violet Ice' stock plants grown under a DLI of 10 to 12 mol·m^{-2}·d^{-1} are 60 and between 1450 and 1850 µmol·m^{-2}·s^{-1}, respectively (Lopez, 2007). Cuttings under the lowest and highest propagation DLI treatments of 1.2 and 8.4 mol·m^{-2}·d^{-1} in the present study were exposed to a maximum irradiance of 91 and 562 µmol·m^{-2}·s^{-1}, respectively, during the 16 d of propagation. Therefore, for most of the 16 d of propagation, cuttings under the lowest DLI were rarely exposed to a light intensity above the LCP, and consequently root biomass accumulation was only 0.10 mg·d^{-1} compared with 1.1 mg·d^{-1} for the cuttings under the highest DLI. Thus, our results indicate that during root initiation of herbaceous cuttings, the DLI should be maintained between 4 and 6 mol·m^{-2}·d^{-1} for photosynthesis and to avoid a delay in root initiation and excessive shoot elongation (Expt. 1, 8 or 10 d of propagation). After root initiation, light levels should be maintained between 6 and 8 mol·m^{-2}·d^{-1} to promote root and shoot biomass accumulation (Expt. 1, 12 to 16 d of propagation).

With our results, root and shoot biomass of these cuttings can be predicted under a range of propagation DLIs (Figs. 1 and 2) with air temperatures of 24 to 25 °C. We previously determined that a fully rooted transplant of petunia 'Tiny Tunia Violet Ice' requires greater than 35 roots and a root and shoot dry weight greater than 10 mg and greater than 65 mg, respectively (unpublished data). Therefore, petunia 'Tiny Tunia Violet Ice' cuttings propagated under a mean DLI of 6 mol·m^{-2}·d^{-1} should be fully rooted within 12 d compared with a cutting rooted under a mean DLI of 3 mol·m^{-2}·d^{-1}, which would take ≈22 d with 1.8 roots/d and root and shoot biomass accumulation of 0.45 and 3.8 mg·d^{-1}, respectively. Similarly, we

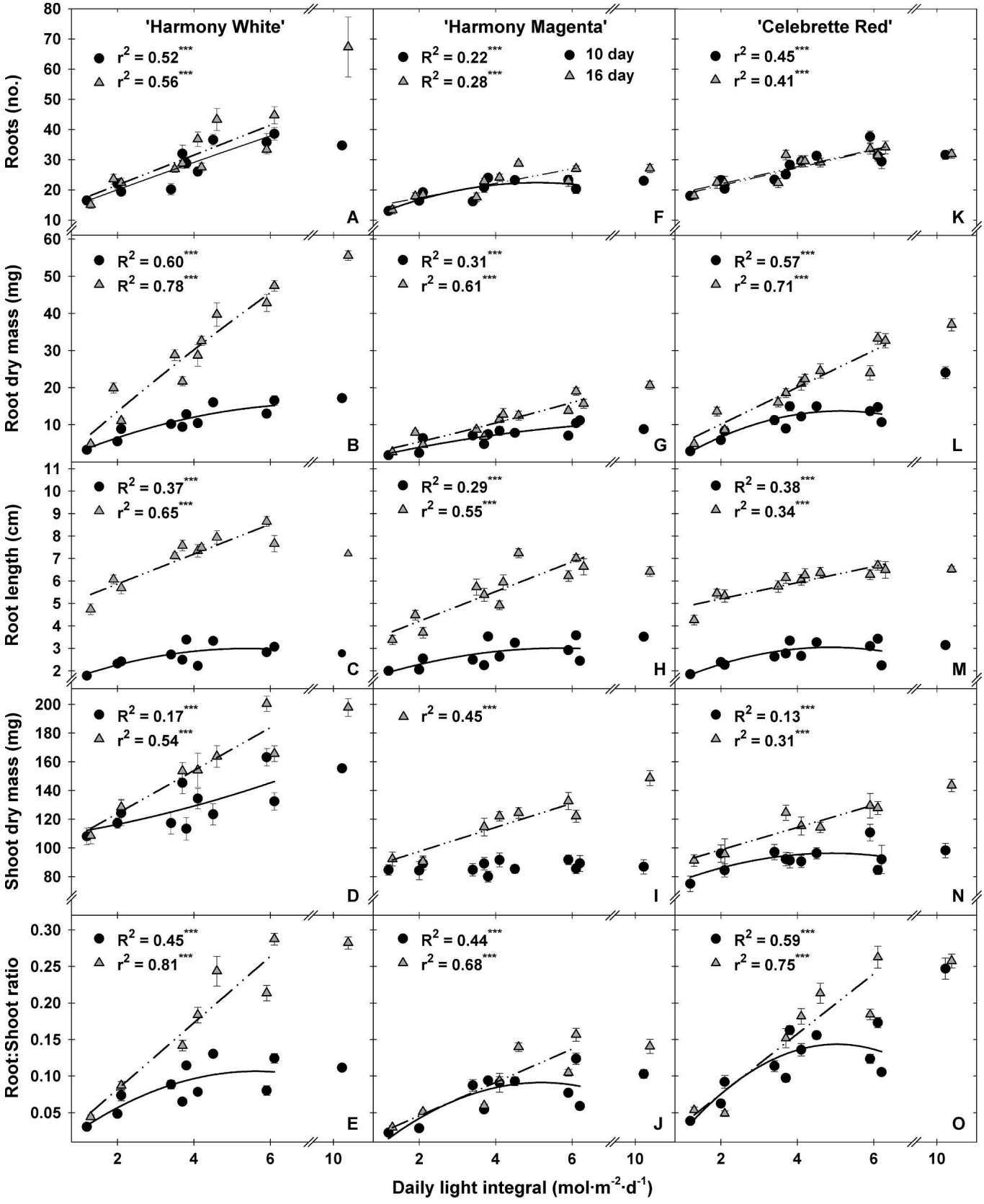

Fig. 3. (**A–O**) Relationships between mean daily light integral and number of roots formed, root dry weight, length of the longest root, shoot dry weight, and root-to-shoot ratio measured after 10 d (shaded circles) and 16 d (open triangles) of propagation for New Guinea impatiens 'Harmony White', 'Harmony Magenta', and 'Celebrette Red' cuttings. 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. Legend in F applies to all figures. ***Significant at $P \leq 0.001$.

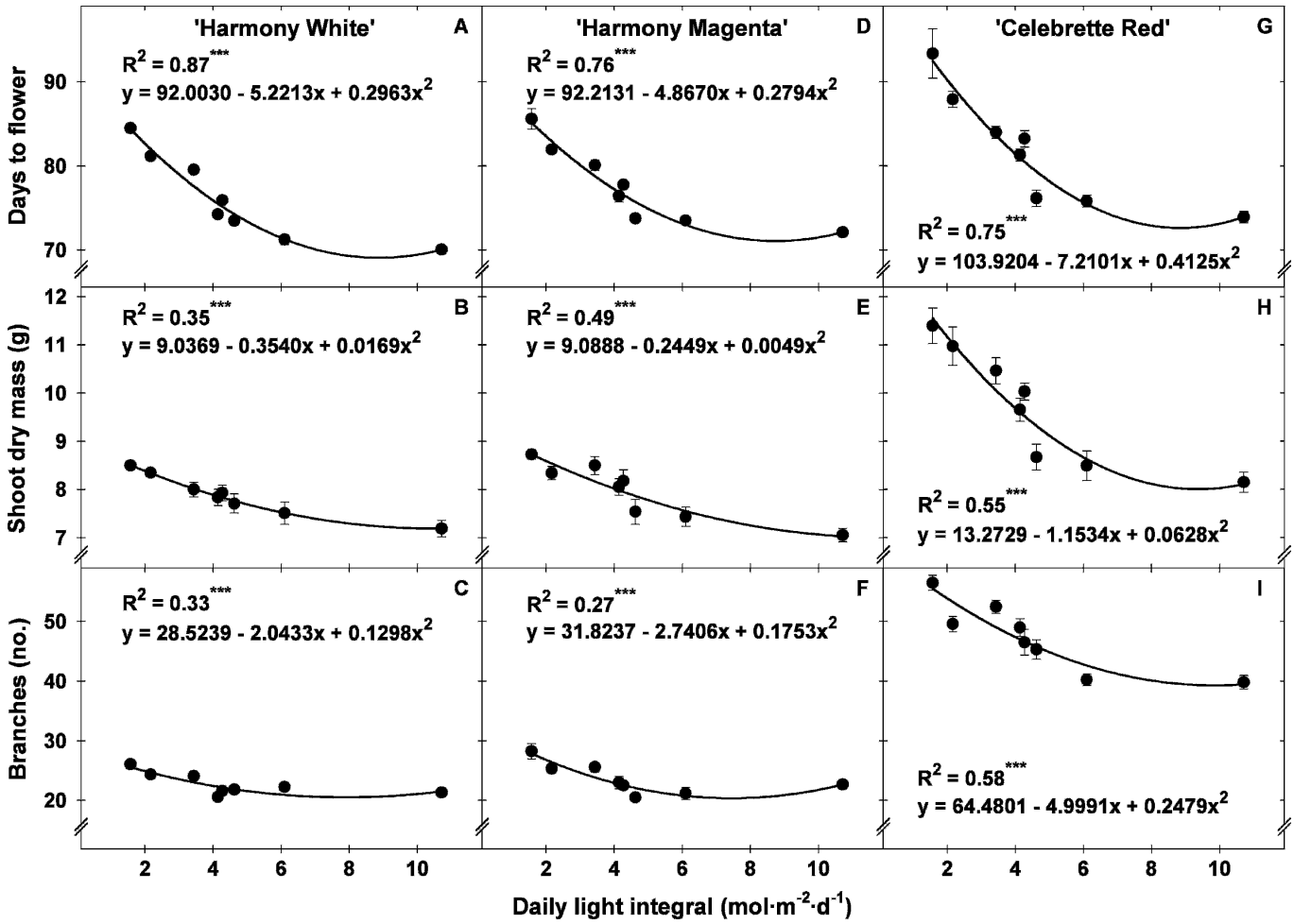

Fig. 4. (**A–I**) Relationships between mean daily light integral during propagation and days to flower from the beginning of propagation, shoot dry weight, and number of lateral branches at first flowering for New Guinea impatiens 'Harmony White', 'Harmony Magenta', and 'Celebrette Red' cuttings. Each symbol represents a mean of 12 plants, and error bars represent SES of the mean. Equations for regression lines are presented with corresponding R^2. ***Significant at $P \leq 0.001$.

previously determined that New Guinea impatiens 'Harmony White' transplants are fully rooted when they have a root and shoot dry weight greater than 30 mg and greater than 150 mg, respectively (unpublished data). Our data predict that root biomass accumulation will occur at 0.86 or 2.9 mg·d^{-1} when cuttings are propagated under a mean DLI of 2 or 6 mol·m^{-2}·d^{-1}, requiring 35 or 13 d of propagation, respectively. Greenhouse propagators of these plants could use our models to improve their prediction of propagation time according to the light levels provided to their crops.

To our knowledge, this is the first study that quantifies the effect of DLI during propagation of vegetative cuttings on subsequent plant performance in a common environment. Subsequent time to flower of 'Tiny Tunia Violet Ice' and 'Supertunia Mini Purple' petunia and all three New Guinea impatiens cultivars decreased as the DLI under which the cuttings were propagated increased within the range of propagation DLIs studied regardless of the finishing DLI. Similarly, Pramuk and Runkle (2005a) demonstrated that increasing DLI during the seedling stage of annual bedding plants accelerated subsequent time to flower independent of the finish DLI. For petunia 'Tiny Tunia Violet Ice' and 'Supertunia Mini Purple', plant mass (expressed as plant shoot dry biomass) and flower bud number at first flowering decreased as propagation DLI increased (Fig. 2). Similarly, plant quality characteristics (shoot dry biomass and number of lateral branches) decreased for all New Guinea impatiens cultivars studied as rooting DLI during propagation increased (Fig. 4). Cuttings propagated under the lower DLI treatments took longer to flower; thus, they had more time to harvest light before flowering, producing more photosynthate for biomass accumulation (e.g., flowers and branches). Similar results have been observed when seedlings or finish plants were grown with either increasing DLI or temperature (Pramuk and Runkle, 2005a, 2005b; Yuan et al., 1998).

We speculate that the 14- to 19-d and 22-d delay in flowering for New Guinea impatiens and petunia, respectively, could be the result of flower bud abortion or carbohydrate depletion. The delay in flowering was within 6 d of the propagation time (16 d), which suggests that flowers were aborting or ceasing to develop when the propagation DLI was low. Alternatively, the carbohydrate status of cuttings under a low DLI could have been depleted during propagation, and additional time after transplant may have been required for plants to accumulate enough photosynthate to promote flowering.

In petunia 'Double Wave Spreading Rose', time to flower was not influenced by propagation DLI but was influenced by finishing DLI (Fig. 2D; Table 2). In replication 1, plants flowered in 48 d when the forcing DLI was 13 mol·m^{-2}·d^{-1}, whereas in replication 2, plants flowered in 63 d when the forcing DLI was 7.4 mol·m^{-2}·d^{-1}, which suggests that this cultivar has a facultative irradiance response. Plants such as 'Double Wave Spreading Rose' that exhibit a facultative irradiance response typically flower earlier when provided with higher light (Erwin et al., 2004). In irradiance-indifferent plants such as 'Tiny Tunia Violet Ice' and 'Supertunia Mini Purple', flower bud initiation occurs regardless of light level and further increases in light during finishing do not hasten flowering.

Our results show the value of maintaining DLI at 4 to 6 mol·m^{-2}·d^{-1} during the first stage

of rooting and 6 to 8 mol·m^{-2}·d^{-1} during the second stage to obtain rapid, uniform rooting and high-quality rooted transplants that flower earlier, especially when cuttings are rooted during the darkest periods of the year. Rapid, uniform, and complete flowering is of primary interest to greenhouse growers so that production time can be minimized. However, our results and those of similar studies (Pramuk and Runkle, 2005a, 2005b) indicate that a tradeoff exists between rapid flowering and high finish-plant quality. Our model can consequently be used to determine how excessive shading, changing DLI, supplemental lighting, and seasonal propagation environments will affect subsequent performance (e.g., flowering time and plant quality). For example, petunia 'Tiny Tunia Violet Ice' and New Guinea impatiens 'Harmony White' cuttings propagated under a mean DLI of 2 and 8 mol·m^{-2}·d^{-1} are predicted to flower in 46 and 33 d and 83 and 69 d, respectively, if subsequently forced at 20 °C.

Literature Cited

Behrens, V. 1988. Influence of light intensity on the propagation success of *Acer palmatum* 'Atropurpureum' propagated by cuttings. Acta Hort. 226:321–326.

Cabaleiro, C. and A.S. Economou. 1992. Effect of light on rooting in vitro of petunia microshoots. Acta Hort. 300:189–196.

Costa, J.M. and H. Challa. 2002. The effect of the original leaf area on growth of softwood cuttings and planting material of rose. Scientia Hort. 95:111–121.

Davis, T.D. and J.R. Potter. 1981. Current photosynthate as a limiting factor in adventitious root formation on leafy pea cuttings. J. Amer. Soc. Hort. Sci. 106:278–282.

Dole, J.M. and D.J. Hamrick. 2006. Propagation basics, p. 3–16. In: Dole, J., and J. Gibson (eds.). Cutting propagation: A guide to propagating and producing floriculture crops. Ball Publishing, Batavia, IL.

Druege, U., S. Zerche, and R. Kadner. 2004. Nitrogen- and storage-affected carbohydrate partitioning in high-light adapted *Pelargonium* cuttings in relation to survival and adventitious root formation under low light. Ann. Bot. (Lond.) 94:831–842.

Eliasson, L. and L. Brunes. 1980. Light effects on root formation in aspen willow cuttings. Physiol. Plant. 48:261–265.

Enfield, A.L. 2002. Flower induction and cultural requirements for quick-cropping of the herbaceous perennials *Veronica spicata, Phlox paniculata, Leucanthemum ×superbum, Achillea, Gaura lindheimeri*, and *Campanula*, Dept. of Horticulture, Michigan State Univ., East Lansing. MS Thesis.

Erwin, J., N. Mattson, and R. Warner. 2004. Light effects on annual bedding plants, p. 62–71. In: Fisher, P., and E. Runkle (eds.). Lighting up profits: Understanding greenhouse lighting. Meister Media Worldwide, Willoughby, OH.

Grange, R.I. and K. Loach. 1985. The effect of light on rooting of leafy cuttings. Scientia Hort. 27:105–111.

Haissig, B.E. 1986. Metabolic processes in adventitious rooting of cuttings, p. 141–189. In: Jackson, M.B. (ed.). New root formation in plants and cuttings. Martinus Nijhoff Publishers, Dordrecht, The Netherlands.

Hanan, J. 1998. Greenhouses: Advanced technology for protected horticulture. CRC Press, Boca Raton, FL.

Islam, N. and K. Willumsen. 2001. Effects of photoperiod and daily light integral on rooting, subsequent growth, flowering and yield of flowering stems in *Gypsophila paniculata* L. 'Perfecta'. Gartenbauwissenschaft 66:225–228.

Kachecheba, J.L. 1976. Seasonal effects of light and auxin on the rooting of *Hibiscus* cuttings. Scientia Hort. 5:345–351.

Korczynski, P.C., J. Logan, and J.E. Faust. 2002. Mapping monthly distribution of daily light integrals across the contiguous United States. HortTechnology 12:12–16.

Lopez, R.G. 2007. Stock plant and propagation photosynthetic daily light integral and storage influences postharvest performance of herbaceous cuttings. Dept. of Horticulture, Michigan State Univ., East Lansing. PhD Diss.

Pramuk, L.A. and E.S. Runkle. 2005a. Photosynthetic daily light integral during the seedling stage influences subsequent growth and flowering of *Celosia, Impatiens, Salvia, Tagetes*, and *Viola*. HortScience 40:1336–1339.

Pramuk, L.A. and E.S. Runkle. 2005b. Modeling growth and development of *Celosia* and *Impatiens* in response to temperature and photosynthetic daily light integral. J. Amer. Soc. Hort. Sci. 130:813–818.

Rapaka, V.K., B. Bessler, M. Schreiner, and U. Druge. 2005. Interplay between initial carbohydrate availability, current photosynthesis, and adventitious root formation in *Pelargonium* cuttings. Plant Sci. 168:1547–1560.

U.S. Dept. of Agriculture. 2007. Floriculture and nursery crops yearbook: Report. Econ. Res. Service, Washington, DC. 27 June 2008. <http://usda.mannlib.cornell.edu/usda/ers/FLO-yearbook//2000s/2007/FLO-yearbook-10-04-2007.pdf>.

U.S. Dept. of Agriculture. 2008. Floriculture crops 2007 summary. Nat. Agr. Sta. Service, Washington, DC, 27 June 2008. <http://usda.mannlib.cornell.edu/usda/current/FlorCrop/FlorCrop-04-24-2008.pdf>.

Veierskov, B. 1988. Relations between carbohydrates and adventitious root formation, p. 70–78. In: Davis, T.D., B.E. Haissig, and N. Sankhla (ed.). Adventitious root formation in cuttings. Dioscorides Press, Portland, OR.

Yuan, M., W.H. Carlson, R.D. Heins, and A.C. Cameron. 1998. Effect of forcing temperature on *Coreopsis grandiflora, Gaillardia ×grandiflora, Leucanthemum ×superbum*, and *Rudbeckia fulgida*. HortScience 33:663–667.