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TEMPERATURE AND DAILY LIGHT INTEGRAL EFFECTS **ON FIVE BEDDING PLANT SPECIES**

presented by

Lee Ann Pramuk

has been accepted towards fulfillment of the requirements for the

M.S. degree in Horticulture

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TEMPERATURE AND DAILY LIGHT INTEGRAL EFFECTS ON FIVE BEDDING PLANT SPECIES

By

Lee Ann Pramuk

A THESIS

Submitted to Michigan State University in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Department of Horticulture

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ABSTRACT

TEMPERATURE AND DAILY LIGHT INTEGRAL EFFECTS ON FIVE BEDDING PLANT SPECIES

By

Lee Ann Pramuk

Production of bedding plants is of major economic importance to the floriculture industry, with >\$1.7 billion wholesale value in the United States. Quantifying how temperature and daily light integral (DLI) influence production of these crops would enable greenhouse growers to improve the accuracy of scheduling crops, as well as identify optimum environments for efficient production. A series of experiments was performed on five popular bedding plant species, Celosia argentea var. plumosa 'Gloria Mix', Impatiens wallerana 'Accent Red', Salvia splendens 'Vista Red', Tagetes patula 'Bonanza Yellow', and Viola ×wittrockiana 'Crystal Bowl Yellow', to determine the effects of temperature and DLI on growth and development during seedling and finish stages. Increasing DLI during the plug stage (from 4.1 to 14.2 mol·m⁻²·d⁻¹) increased initial plug quality (dry weight per node), and decreased subsequent time to flower. Models relating temperature (from 14 to 27 °C) and DLI (from 4 to 26 mol·m⁻ $^{2}\cdot d^{-1}$) to time to finished plug and flowering were developed. For example, as temperature increased from 14 to 27 °C, Tagetes time to flowering decreased by 18 days under 5 mol \cdot m⁻²·d⁻¹ and by 12 days under 25 mol \cdot m⁻²·d⁻¹. Effects of temperature and DLI on flower size, flower number, dry weight, node number, and height were also quantified.

DEDICATION

In memory of Ronald Pramuk.

Your love and support are with me still.

Your courage, bravery, and love of life taught me volumes.

Each day, let us make a beautiful and great memory, as if it were to be the last we'll

ever share.

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ACKNOWLEDGEMENTS

To my major professor, Dr. Erik Runkle, I extend my sincere thanks and appreciation for guidance, support, and advice. To my other committee members, Dr. Jeff Andresen and Dr. Royal Heins, I thank you for your valuable insight and guidance.

Also, I wish to thank the greenhouse growers who support Michigan State floriculture research and the Michigan Agriculture Experiment Station for financial assistance. A special thank you to Allen Pyle and Raker's Acres for plant material and advice.

I extend a special thank you to the floriculture greenhouse technicians, Dave Joeright and Mike Olrich for their assistance in experimental setup and for always providing much needed laughter and singing. Thank you to Matt Steinkopf for assistance in data collection and always making me smile. To my fellow graduate students and officemates, Grete Waaseth, Janelle Glady, Roberto Lopez, Marcus Duck, and Charlie Rohwer, thanks for helping to make work an interesting and enjoyable place. To my roommate and best buddy, Ann, thank you for keeping me grounded.

A big thank you to my family, Mom, Matt, Kris, Dave, Angie, Jim, and Abigail. Your support and love are an inspiration and I couldn't have made it without you!

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Introduction

Production of garden plants is of major economic importance to the floriculture industry. In 2000, greenhouse growers in the United States produced garden plants with a wholesale value of \$2.12 billion, representing 50% of the wholesale value of all reported floricultural crops (USDA, 2001). At the state level, Michigan ranked third in sales of wholesale floriculture products in 2000, only after California and Florida. In Michigan, 726 growers reported gross sales greater than \$10,000, and their estimated collective wholesale value was \$301 million for all surveyed floriculture crops. Of the \$301 million, \$148 million was attributed to the sale of garden plants (MDA, 2001).

The production of spring bedding plants in relatively cold climates like Michigan forces growers to rely on greenhouse heating in the winter and early spring. In recent years, fuel prices have fluctuated dramatically. For example, prices of natural gas in 2000 and early 2001 were at record high levels due to a large increase in demand without a corresponding increase in supply. In 1990, the average price of natural gas sold to commercial consumers was \$6.52 per thousand cubic feet (adjusted for inflation), and in September 2001, the average price was \$8.99 per thousand cubic feet (EIA, 1999; EIA, 2001). In response to energy expenses, some growers have lowered their thermostats to reduce their monthly heating bills; others have used supplemental photosynthetic lighting in combination with lower temperature set points. Although these methods could save in short-term fuel costs, crop timing and plant quality may be compromised in the process. Crop timing is of paramount importance for growers because many floricultural products are only marketable within narrow time frames. For example, Easter lilies (*Lilium longiflorum* Thunb.) are sold during the 10-day

p ir th m ha (P (C et pro are am ten (Ac tem tem and kno[,] Publ (Imp period before Easter, and afterward, there is no demand for the crop. Plant quality is important because it often determines the value and marketability of the crop.

Due to the value of bedding plants and the need for energy efficient production, the growth and development of bedding plants as a function of environmental variables must be well understood and quantified. The effects of temperature and light intensity have been studied on some economically important floricultural crops, such as petunia (Petunia ×hybrida Hort.Vilm.-Andr.), pansy (Viola ×wittrockiana Gams.), vinca (Catharanthus roseus L.), and seed geranium (Pelargonium ×hortorum Bailey) (Adams et al., 1997; 1999; Armitage et al., 1981; Pietsch et al., 1995). Although these studies provide information on plant response to temperature and light, more research in this area is warranted due to the variability of optimum temperatures and light requirements among species and between developmental processes. For example, optimum temperature for shortest time to flower of pansy is 21.7 °C, but it is \approx 35 °C for vinca (Adams et al., 1997; Pietsch et al., 1995). An example of the variability of optimum temperature between developmental processes is observed in vinca; the optimum temperature for flower size is 25 °C, while the optimum temperature for leaf unfolding and stem elongation is about 35 °C (Pietsch et al., 1995). Additionally, to our knowledge, few scientific studies on temperature and irradiance interaction have been published on other economically important floricultural crops, such as impatiens (Impatiens wallerana Hook.f.) and marigold (Tagetes patula L.).

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Temperature Effects on Plant Growth and Development

Plant growth rate and morphological development are highly regulated by temperature. Each plant species responds to a different set of temperatures, a minima, maxima, and optima, called the cardinal temperatures. Growth rate is zero at or below the base temperature, T_b , and is maximal at the optimum temperature, T_{opt} . Growth stops at some maximum temperature, T_{max} , and beyond that temperature plant death may result (Fig. 1). Between T_b and T_{opt} , the rate of plant development is typically assumed to be linear (Salisbury and Ross, 1992). The values of T_b , T_{opt} , and T_{max} are all species specific. Examples are listed in Table 1.



Figure 1. A model relating rate of development as a linear function of temperature.

Many chemical processes occur simultaneously in a plant, each having its own optimal temperature. The factor by which a reaction increases with a 10 °C increase in temperature is called the Q_{10} . For example, the Q_{10} for respiration of hybrid geranium leaves is about 2.2, determined between 17 and 27 °C (Armitage et al., 1981). Thus,

Table 1. Quantitative growth and developmental information for various floricultural plants. DLI= daily light integral (mol-m⁻²·d⁻¹): T = average daily temperature (°C), unless noted.

																		2	
	Reference	(Karlsson, 1992)	(Niu et al., 2001								(Pietsch et al.,	1995)						(Yen et al., 1993	
	T _{max}	21																39.8	37.1
	T																	19.3	22.3
	T _{base}	≈10	-19	-2	6-						≈10	≈12	≈11	6≈	≈10	6≈		1.6	1.7
number of the second se	Equation	Y= - 0.2083 + 0.03145*T - 0.0007631*T ²	Y= 0.00111*T + 0.02146	Y= 0.00189*T + 0.00340	Y= 0.00073*T + 0.00657	DLI = 15.8; Y = -1.07*T + 63.68	DLI = 10.8: $Y = -0.97*1 + 61.58DLI = 4.2$: $Y = -0.82*T + 51.58$	DLI = 15.8: Y= -10.43*T + 365.33	DLI = 10.8 : Y = -10.49 *T + 330.74 DLI = 4.2 : Y = -3.81 *T + 114.17	DLI = 15.8: $Y = -0.29*T + 10.23$ DLI = 10.8: $Y = -0.27*T + 8.88$	50% Shade: Y= -0.079 + 0.0079*T	Ambient: $Y = -0.126 + 0.0106*T$	Supplemental Light: Y= -0.135 + 0.0122*T	50% Shade: Y= -0.0151 + 0.0017*T	Ambient: $Y = -0.0198 + 0.0019*T$	Supplemental Light: Y=-0.0178 +	0.002*T	Y = -0.0129 + 0.0082 * T	Y = -0.00307 + 0.00176*T
temperature (°C), unless r	Developmental process	Leaf unfolding rate under long day conditions (16-h)	Rate of progress from forcing to visible bud	Rate of progress from visible bud to flowering	Rate of progress from forcing to flowering	Flower diameter (mm)		Flower bud number		Dry mass (g/plant)	Leaf unfolding rate			Days to flower	•			Rate to visible bud	Rate from visible bud to anthesis
i aule 1. Quanulauve g d ⁻¹): T= average daily	Name	Begonia ×hiemalis Fotsch 'Hilda' and 'Ballet'	<i>Campanula carpatica</i> Jaca, 'Blue Clips'		<u>.</u>						Catharanthus roseus L.	'Grape Cooler'						Cineraria L.'Cindy	Blue'

Table 1. Onantitative growth and developmental information for various floricultural plants. DLI= daily light integral (mol-m-

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Developmental process
Name

	Developmental process	Equation	T _{bac}	T	T	Reference
	Rate of forcing to visible bud	Y= -0.0181 + 0.00275*T	6.6			(Yuan et al., 1998)
	Rate of visible bud to flower	Y= -0.0235 + 0.00347*T	6.8			
	Rate of forcing to flower	Y=-0.0105 + 0.00155*T	6.8			
1	Shoot emergence of tubers	$Y = 65.05 - 4.8126 * T + 0.098 * T^2$				(Kanellos and
	Days to flower	Y= 122.8 – 3 .86*T + 0.089*T ²				Pearson, 2000)
-	Flower area (cm²)	Y= 26.496 – 0.673*T				
	Plant height at flower	Y = -1.309 + 1.062 * T				
	Leaf-pair unfolding rate		5.5	24.6	34.9	(BrØndum and
	Rate pinch to visible bud		2.4	22.4	31.1	Heins, 1993)
	Rate visible bud to flower		5.2	24.2	33.1	
	Flower diameter (mm)	Y= 86.32 - 1.42*T				
	Node Number	Y= 3.01 + 0.1236*T				
	Duration of short days to	$(T_1 = temperature from start of SD to$				(Karlsson et al.,
	visible bud	beginning of considered phase. $T_2^{=}$				1989)
		temperature during considered phase)				
		$Y = 107.6160 - 7.0448*T_1 + 0.1650*T_1^2$				
	Duration of visible bud to	$Y = 105.6318 - 2.0318* T_1 - 3.2967*T_2$				
	disbud	$+ 0.0305 * T_1^2 + 0.1337 * T_2^2 - 0.2039$				
		$(T_1 * T_2) + 0.0049[T_2^{2*}T_2]$				
	Duration of disbud to first	$\mathbf{Y} = 44.6060 - 1.9315 \mathbf{*T}_{1} - 1.8386 \mathbf{*T}_{2} + 1$				
	color	$0.0500*T_1^2 + 0.0403*T_2^2 - 0.0054$				
		$(T_1^*T_2) - 0.0001[T_1^*T_2^2]$				
	Duration of first color to	$\mathbf{Y} = 30.6927 - 0.2680*T_{\lambda} - 1.6791*T_{2} +$				
	flower	$0.0279*T_1^2 + 0.0291*T_2^2 - 0.0279*T_1^2 = 0.0279*T_1^2 - 0.0279*T_2^2 = 0.0279*T_1^2 = 0.0277*T_1^2 = 0.0079*T_1^2 = 0.00$				
		$0.0017(T_1*T_2^2) - 0.0018(T_2^{2*}T_2)$				
	Leaf unfolding rate per hour	Y = (-0.01447 + 0.001917*T - 0.001917)	10	56		(Berghage et al.,
	(after appearance of first 3	0.00003904*T ²)				(0661
	leaves)	T=average temp for 1 hour				
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Reference	(Yuan et al., 1998)			(Karlsson et al.,	(0661	(Yuan et al.,	(0//1			(Karlsson et al., 1988)	(Armitage et al., 1981)			(Pitlinski and	Krug, 1989)					(Kaczperski et al.,			
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F	- 0.5	9.6	3.3	9.8		-13.1	6.0		-3.4	1:1													
Found	Y = 8.39 + 1.46*T	Y = -6.21 + 6.46*T	Y = -4.28 + 1.25 * T	Leaves $d^{-1} = 0.0629 - 0.0202625 + T$	$0.0017*T^2 - 0.00003*T^3$	Y = 0.0171 + 0.00128*T	V = _0 00417 +0 00219*T		Y = 0.00306 + 0.000874*T	Leaves d ¹ = -0.1052 + (0.0940*T)	Y= 181.1 - 11.9*T + 0.21*T ²	$Y = 0.24 + 0.49*T - 0.02*T^2$	$Y = 681.9 - 40.5 * T + 89 * T^2$	$(\Delta T = day temperature - night$	temperature)	Y = -8.90+1042.1/(T-1.9)-0.13	ΔT-0.8 * (21.7-T)	Y = $-388.7 + 26641/(T+27.8)$ -	4.2* ΔT-3.5	DLI = 13: Y=190.205 - 11.1917*T	$P_{1} = 6.5; Y = 212.741 - 11.7045*T + DLI = 6.5; Y = 212.741 - 11.7045*T + DLI = 6.5; Y = 212.741 - 11.7045*T + 0.55 +$	0.211953*T ²	DLI = 13: Y= 9.2607- 0.00634*T ² DLI = 6.5: Y=8.85987- 0.00723*T ²
Davalonmental morece	Rate of forcing to visible bud	Rate of visible bud to flower	Rate of forcing to flower	Leaf unfolding rate		Rate of forcing to visible	Dud Dote of visible build to	flower	Rate of forcing to flower	Leaf unfolding rate	Days from bud to flower	Flower diameter	Leaf thickness (µm)	Days to anthesis as a	function of day and night	temperature		Fresh weight at anthesis		Days to flower			Number of lateral breaks
	Gaillardia ×grandiflora (Van Houtte) 'Goblin'			Hibiscus rosa-sinensis	L. 'Brilliant Red' and 'Pink Versicolor'	Leucanthemum	xsuperbum Bergman	ex. J. Ingrani Showcap		Lilium longiflorum Thunb. 'Nellie White'	Pelargonium × hortorum Bailev	'Sooner Red'		Pelargonium zonale L.	'Mars'					Petunia × hybrida Vilm.	-Andr. Snow Cloud'		
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Reference	(Steininger et al., 2002)							(Yuan et al.,	(864)			(Faust and Heins,	1993)	(Erwin et al.,	(0661		(Pearson et al.,	1995)	(Adams et al., 1997)
T												30.8						25	
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Thase		10.5	6.2	9.5	9.0	4.5	8.1	-1.3		5.1	-1.3	8		-9.3					
Equation	$Y = 30.6927 - 2680T_1 - 1.6791*T_2 + 0.0279*T_1^2 + 0.0279*T_1^2 + 0.0291*T_2^2 - 0.0017 (T_1^* + T_2^2) - 0.0018 (T_2^2*T_2)$							Y = 0.00126 + 0.000965*T		Y = 0.00514 + 0.000985*T	Y = 0.000687 + 0.000528*T	Leaf count = 0.244 * Days - 0.302		$Y = 5817.57 * e^{(-0.3591*x)} + 49.3$			Y = 35.3 - 1.05T	Y = 23.5 - 0.42 T	(M= DLI, MJ· m ⁻² · d ⁻¹) Y = -0.01364 + 0.00434*T + 0.01826*M
Developmental process	Duration of first color to flower	Budbreak to visible bud	Visible bud to open flower	Budbreak to open flower	Budbreak to visible bud	Visible bud to open flower	Budbreak to open flower	Rate of forcing to visible	pnq	Rate of visible bud to flower	Rate of forcing to flower	Leaf unfolding rate at 22 °C	and DLI=7	Days from induction to	anthesis	Flower initiation	Flower area (cm ²)	Days from visible bud to	Leaf unfolding rate
Name	Rosa sp. L.	'Candy Sunblaze'			Ked Sunoiaze		8	Rudbeckia fulgida (Ait.)	'Goldsturm'		•	Saintpaulia ionantha	Wendl. 'Utah'	Schlumbergera truncata	Haw. 'Madisto'		Viola xwittrockiana	Gams. 'Universal Violet'	

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for geranium leaves, the reaction rate of respiration approximately doubles for an interval of 10 $^{\circ}$ C.

Tissues within the same plant may respond to temperatures differently because different chemical processes have unique optimal temperatures. A classic example is a study by Julius Van Sachs in 1863. He demonstrated differing optimal temperatures for upper and lower tepal growth of tulips (*Tulipa* sp. L.) and crocus (*Crocus* sp. L.) Lower tepal growth was optimal at 3 to 7 °C while upper tepal growth was greatest at 10 to 17 °C. This allows the flowers to close at cooler temperatures and open at warmer temperatures (Salisbury and Ross, 1992).

Vegetative Development and Temperature

The rate of vegetative development increases with increasing temperature. One way to quantify vegetative development is by the leaf unfolding rate. This is the number of leaves that unfold per unit of time, for example leaves d⁻¹. Knowing the leaf unfolding rate of a species can help time crops to meet specific finish dates.

In many species, as average temperature increases, leaf unfolding rate increases in a linear fashion until T_{max} is reached (Moe and Heins, 1990). For example, this relationship is observed in hibiscus (*Hibiscus rosa-sinensis* L. 'Brilliant Red' and 'Pink Versicolor') (Karlsson et al., 1990). A linear function approximated the leaf unfolding response from 11 °C to 30 °C, and maximum leaf unfolding occurred at 32 °C with 0.229 leaves per day; beyond this point, leaf unfolding decreased (Karlsson et al., 1990). There was no difference in leaf unfolding rate for the two cultivars of hibiscus (Karlsson et al., 1990). Also, the leaf unfolding model was validated with three other cultivars, 'Florida Sunset', 'Painted Lady', and 'Euterpe'. Similar linear responses have been observed in chrysanthemum, easter lily, and vinca (Karlsson et al., 1989,1988; Pietsch et al., 1995).

Karlsson (1992) studied the leaf unfolding rate in hiemalis begonia (*Begonia* ×*hiemalis*, 'Hilda' and 'Ballet'). Long days promoted vegetative growth and short days induced reproductive growth (Karlsson, 1992). Under long days, both cultivars had similar unfolding rates when grown at 13 to 28 °C, with maximum leaf unfolding of 0.116 leaves·d⁻¹ at 21 °C. A quadratic function was used to describe the 16-h long day leaf unfolding rate. Under 10-h short days 'Ballet' continued to unfold at the same rate as under 16-h long day conditions, but 'Hilda' decreased to half the rate observed under long day conditions, illustrating differing cultivar responses to photoperiod.

Leaf unfolding rate has also been determined for poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch 'Annette Hegg Dark Red'). Because poinsettias are grown vegetatively before flower initiation, Berghage et al. (1990) modeled leaf unfolding rate from the time of pinching to the appearance of the first three leaves (LAG) and also the subsequent leaf unfolding rate (LUR). LAG was negatively correlated with temperature; as average temperature increased from 18 °C to 29 °C, LAG decreased by approximately 7 days. Subsequent leaf unfolding rate ranged from 0.132 leaves d⁻¹ with an average daily temperature (ADT) of 15.3 °C to 0.245 leaves d⁻¹ with an ADT of 27.8 °C. Day and night temperatures had equivalent effects on poinsettia in both LAG and LUR (Berghage et al., 1990).

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Flowering

Because flower organogenesis and development are largely under metabolic control, the importance of temperature at this stage is basic to the rate of flower development for all bedding plants (Armitage, 1994). Thus, when plants reach visible bud stage, flowering is controlled by temperature more than any other environmental variable (Armitage, 1994).

Kacsperski et al. (1991) showed that the number of days to flower for petunia (*Petunia* ×*hybrida* 'Snow Cloud') was a quadratic function of average temperature with an optimum temperature of 25 °C when grown under 13 mol·m⁻²·d⁻¹ and an 18-h photoperiod. In vinca, average daily temperature controlled days to flower and flower development rate; time to flower decreased by 30 days as average daily temperature increased from 18 to 35 °C (Pietsch et al., 1995).

Different phases of flowering can also have different optimum temperatures. In chrysanthemum 'Bright Golden Anne' (*Dendranthema grandiflora* Tzvelev.), four developmental stages were studied: (1) from start of short days to visible bud, (2) visible bud to disbud, (3) disbud to first color, and (4) first color to flower (Karlsson et al., 1989). Optimum temperatures for these stages were 21.3, 20.3, 23.1, and 19.1 °C, respectively. Additionally, plants may exhibit temperature conditioning; the temperature the plant receives in initial stages of development may influence subsequent stages of development. Temperature extremes of 10 or 30 °C during the first and second stage of development of chrysanthemum delayed the time to complete the third

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stage of development. However, the fourth stage was unaffected by initial unfavorable temperatures (Karlsson et al., 1989).

Temperature Effects on Plant Quality

Temperature profoundly affects plant quality, or the aesthetic appeal of the plant. Some quantifiable indicators of plant quality that are affected by temperature are branching, flower number, flower diameter, and plant biomass.

Branching

One characteristic of high quality plants is desirable plant architecture. Generally, plants grown at cooler temperatures exhibit more branching than those grown at warmer temperatures. For example, petunia 'Snow Cloud' grown at a 27 ± 3 °C day temperature (DT) and 7 °C night temperature (NT) had four more basal branches 75 days after seed sow than those grown at 27 ± 3 °C DT/18 °C NT (Merritt and Kohl, 1989). However, flowering was delayed by 10 days when grown at the cooler NT (Merritt and Kohl, 1989). Kaczperski et al. (1991) demonstrated that the number of lateral shoots at flowering formed by petunia 'Snow Cloud' decreased quadratically as day temperature increased; as average temperature increased from 10 °C to 30 °C, the number of lateral shoots decreased from ≈ 8.5 to ≈ 3 .

Although research has shown that cooler temperatures can promote lateral branching, short exposures to very high temperatures after pruning can suppress primary shoot growth and promote lateral shoot growth. Higuchi et al. (1987) explored the relationship between the duration of high temperature exposure, greater than 45 °C (6 to 8 °C higher than the ambient control conditions), and the promotion of lateral

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shoot growth in salvia (*Salvia splendens* F. Sellow ex Roem. & Schult. 'St. John's Fire') and impatiens (*Impatiens sultanii* Hook. f. 'Super Elfin Blush') after pruning. After 4 weeks, high-temperature treated salvia primary shoots were $\approx 57\%$ shorter than control plants. Lateral shoot growth increased in salvia and impatiens; maximum growth of lateral shoots was attained at 850 °C × hour of high temperature for salvia and 400 °C × hour for impatiens, when expressed as integrated temperature above 30 °C (Higuchi et al., 1987). Also, in salvia, the percentage of flowering shoots under high temperatures increased from 40 to 62% and the mean length of the inflorescence increased from 5 to 11 cm measured 65 days after pruning as compared to the control (Higuchi et al., 1987).

Flower Number

A large number of flowers generally make plants more attractive to the consumer, and thus potentially more valuable. In seed impatiens, flower number, when recorded after 4 weeks in temperature treatments, was lower at cooler temperatures (24 °C DT/18 °C NT) than at higher temperatures (30/24 °C DT/NT and 35/30 °C DT/NT) due to slower bud development and opening rates at the cooler temperatures, indicating a thermal time relationship (Lee et al., 1990). For example, *Impatiens* 'Accent Pink' had 50 and 48 flowers in the higher temperature treatments, and 24 flowers in the lower temperature treatment (Lee et al., 1990). Other impatiens cultivars, such as 'Accent Rose', 'Dazzler Pink', and 'Super Elfin Rose' exhibited similar results.

Flower bud number at first flowering of coreopsis (*Coreopsis grandiflora* Hogg ex Sweet. 'Sunray'), rudbeckia (*Rudbeckia fulgida* Ait. 'Goldsturm'), and Shasta daisy

(Leuc and 5 1998) of flo from Flowe growr tempe compa the rej flower detern tempe tempe flower flower quadra 15 °C 1981). (*Leucanthemum* ×*superbum* Bergman ex. J. Ingram 'Snowcap') decreased 80%, 75%, and 55%, respectively, as temperature increased from 16 °C to 26 °C (Yuan et al., 1998). In a study on campanula (*Campanula carpatica* Jacq. 'Blue Clips'), the number of flower buds decreased linearly, at -10 flowers per °C as plant temperature increased from 16 to 24 °C (under ambient CO₂ concentration) (Niu et al., 2001).

Flower Size

In general, mature flower size decreases as the temperature at which plants are grown increases. Lee et al. (1990) demonstrated that impatiens grown at a high temperature regimen (35 °C DT/30 °C NT) for four weeks had smaller flowers compared to those grown at a low temperature regimen (24 °C DT/18 °C NT), and that the relative decrease in size differed among cultivars. Cultivars had 13 to 33% larger flowers at the cooler temperatures.

Similar results were observed with pansy 'Universal Violet'; flower size, determined 4 days after anthesis, decreased linearly from $\approx 25 \text{ cm}^2$ to $\approx 5 \text{ cm}^2$ as temperature increased from 9 °C to 31 °C (Pearson et al., 1995). Additionally, temperature delivered from visible bud to flowering had the most influence on final flower size, and longer durations of higher temperatures led to progressively smaller flowers (Pearson et al., 1995). Geranium 'Sooner Red' flower diameter had a quadratic relationship with temperature (Table 1); flower size was greatest ($\approx 4.8 \text{ cm}$) at 15 °C and decreased (to $\approx 2.8 \text{ cm}$) as temperature increased to 32 °C (Armitage et al., 1981).

based c 2001). plants g Temper species 35 °C, 35 °C, [Cosmo to ≈7.5 2000). decreas in Core Plant I impatie general after 4 'Accen from 3 *Campanula* 'Blue Clips' and 'Birch Hybrid' showed differences in flower size based on the temperature treatment during specific times of development (Niu et al., 2001). Flower size was negatively correlated with ADT after visible bud; flowers on plants grown at 14 °C were 35% larger than those on plants grown at 26 °C. Temperature before visible bud had only a small effect on final flower size in both species (Niu et al., 2001).

When grown under supplemental lighting at a range of temperatures from 15 to 35 °C, vinca flower diameter was greatest (\approx 4.3 cm) at 25 °C (Pietsch et al., 1995). At 35 °C, flower diameter decreased to \approx 3.8 cm (Pietsch et al., 1995). Similarly, Cosmos [*Cosmos atrosanguineus* (Hook) Voss] flower area decreased linearly from \approx 17.5 cm² to \approx 7.5 cm² as temperature increased from 13 °C to 26 °C (Kanellos and Pearson, 2000). In a separate study, as temperature increased from 16 to 26 °C, flower diameter decreased by 2.7 cm (\approx 33%) in *Leucanthemum* and *Rudbeckia* and by 0.9 cm (\approx 16%) in *Coreopsis* (Yuan et al., 1998).

Plant Mass

Plant mass is used as a measure of the overall size and vigor of the plant. In impatiens, plant canopy size (average of plant width and height) and shoot dry weight generally increased as temperature increased from 24/18 °C DT/NT to 35/30 °C DT/NT after 4 weeks, showing a thermal time difference (Lee et al., 1990). For example, 'Accent Red' plant size increased from 20.3 to 26.6 cm, and shoot dry weight increased from 3.95 to 4.42 g as temperature increased (Lee et al., 1990).

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Plant Height

Producing compact plants is desirable for shipping and general aesthetic value; temperature and the difference between DT and NT (DIF) can affect plant height. In many species such as *Lilium longiflorum* Thunb., *Campanula isophylla* Moretti., *Fuchsia* ×hybrida Hort. ex Vilm., and *Dendranthema grandiflorum* Ramat.(Kitamura), a higher NT than DT results in shorter internodes compared to when NT< DT (Erwin and Heins, 1995).

Geranium 'Red Elite' and 'Cardinal Orbit' grown at a 7 °C NT were more compact and were $\approx 50\%$ shorter than those at an 18 °C NT when measurements were recorded after 67 days, but flowering was delayed by 3 weeks (Merritt and Kohl, 1989). In a separate study, geranium 'Encounter Red' was 1 to 2 cm shorter at flowering with a NT of 13 °C compared to17 °C NT, under different light regimens (Tsujita, 1981). However, results of both studies are confounded with the developmental stage in which height measurements are taken. Measurements taken at the same time during the experiment show differences due to thermal time, but the plants may be at different developmental stages (i.e., some may be vegetative under cooler temperatures while those grown warmer may be reproductive).

Cosmos plant height at first flower doubled as temperature increased from 13 °C to 26 °C (Kanellos and Pearson, 2000). In contrast, height of *Rudbeckia* at first flowering decreased by 50% (from \approx 48 cm to \approx 24 cm) as temperature increased from 16 to 26 °C (Yuan et al., 1998). Plant height of *Leucanthemum* also decreased by \approx 15

cm (2 Leuco DIF. tempe rangi DLI (highe were natura promo Light in the to 60 j 2002). wester Octobe more to The ma autumn cm (27%) with increasing temperature (Yuan et al., 1998). In the study of *Leucanthemum* and *Rudbeckia*, the decrease in height may have been influenced by DIF.

Campanula carpatica 'Blue Clips' plant height was not affected by average daily temperature, but increased linearly as DIF increased from -6 to 12 °C under DLIs ranging from 4.2 to 15.8 mol·m⁻²·d⁻¹, with the strongest response being under the low DLI (Niu et al., 2001). However, this response may have been partially affected by the higher red to far red ratio under the high light treatments in this experiment; HPS lights were used in the higher light treatments and have a greater red to far red ratio than natural sunlight. Red light has been shown to reduce elongation whereas far red light promotes stem elongation (Niu et al., 2001).

Light Integral Effects on Growth and Development

Daily light integral varies by latitude and by time of year. Outdoor mean DLI in the U.S. ranges from 5 to 10 mol·m⁻²·d⁻ⁱ across the Northern U.S. in December to 55 to 60 mol·m⁻²·d⁻¹ in the Southwestern U.S. in May through July (Korczynski et al., 2002). The primary DLI differences from May through August between the eastern and western U.S. are due to regional weather patterns, and to some extent, elevation. From October through February, differences between the northern and southern U.S. are due more to differences in solar duration and quantum fluxes (Korczynski et al., 2002). The most rapid changes in DLI occur during the months surrounding the vernal and autumnal equinoxes (Korczynski et al., 2002).

sola obst Lans (Niu trans gree year °N la (Niu Dully Light Integral (mol m²d⁻¹) 0 01 05 05 05 05 05 0 Rate c of gree and fl_0 The amount of light plants receive in a greenhouse is affected by the amount of solar radiation and also the interference from greenhouse glazing, structures, and other obstructions. For example, natural light levels outdoors in midsummer in East Lansing, Michigan average about 45 mol·m⁻²·d⁻¹, and in midwinter about 10 mol·m⁻²·d⁻¹ (Niu et al., 2001). Due to glazing and structures, and shading during the summer, light transmission is often reduced by about 65 to 75%. So, a typical glass-glazed greenhouse in Michigan will transmit an average of about 6 to 25 mol·m⁻²·d⁻¹ during the year. Figure 2 illustrates and example of the differences between DLI observed at 43 °N latitude, and also differences inside and outside of a greenhouse (Niu et al., 2001).



Figure 2. Average daily light integral in East Lansing, MI (43 °N latitude) and Phoenix, AZ (33 °N latitude) outside and inside a typical greenhouse (Niu et al., 2001).

Rate of Flower Development and DLI

A positive effect of high irradiance on flowering has been reported for a number of greenhouse crops, but the importance of supplementary lighting for floral evocation and flower development seems to differ considerably among species (Moe, 1997). The

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rate of floral development partly depends on available photosynthates, so floral development can be inhibited or delayed under low light intensities.

The effects of supplemental light on the rate of development have been studied extensively on geranium (*Pelargonium* ×*hortorum* L.H. Bailey). A study performed by Craig and Walker (1963) confirmed that the flowering of seedling geraniums was influenced by cumulative solar energy, and not simply the number of days from transplanting to flowering. Non-pinched plants grown at the same temperatures (13 °C NT/18 °C minimum DT) at different times of the year, hence different light intensities, had different number of days to flower, but required similar amounts of cumulative solar energy to flower [\approx 55,000 g-cal/cm² (outdoor)].

More recent studies have provided similar results. Erickson et al. (1980) observed in geranium 'Sprinter Scarlet,' 'Sprinter White', and 'Ringo' that average daily cumulative energy levels influence flowering. Forty-one to 65% of the variability in days to flower was associated with cumulative solar energy, which is confounded with temperature. This study also indicated that days to flower may decrease with increasing light intensity at low light levels until a threshold level ($\approx 7 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) is reached.

In a separate study by Armitage and Tsujita (1979), four seed propagated cultivars of geranium ('Sprinter Scarlet', 'Carefree Crimson', 'Carefree Bright Pink', and 'Carefree Dark Salmon') were studied to determine the effect of supplemental light source and quantum flux density on flowering. Plants were grown under 32 or 64 μ mol·m⁻²·s⁻¹ from high pressure sodium (HPS) lamps and 27 or 54 μ mol·m⁻²·s⁻¹ from low

press seed comp The flowe week 6 wee from Crims do noi and 2. to visi above acceler earlier 60% st flower 1984). shaded ; ^{shade} m pressure sodium (LPS) lamps for 2, 4, or 6 weeks. Regardless of cultivar, days from seed to flowering were reduced by at least 11 days under 6 weeks of HPS lighting compared with ambient light alone, but there was no reduction under LPS lighting. The promotion of supplemental lighting varied by cultivar; 'Carefee Bright Pink' flowered earlier with six weeks of low intensity HPS lighting and with 2, 4, and 6 weeks of high intensity light while 'Carefree Deep Salmon' only flowered earlier under 6 weeks of high intensity HPS lighting. Cumulative supplemental quanta (mol·m⁻²) from HPS was negatively correlated with days to flower of 'Sprinter Scarlet', 'Carefree Crimson', and 'Carefree Deep Salmon'.

Although some geranium cultivars flower earlier with an increase in DLI, others do not. For example, 'Red Elite' seed geraniums under DLI treatments of 15.1, 19.8 and 24.6 mol \cdot m⁻²·s⁻¹ from sixth leaf stage to visible bud, showed no differences in time to visible bud (White and Warrington, 1984). However, 15 mol \cdot m⁻²·s⁻¹ may have been above a threshold DLI, which could explain why further increases in DLI may not have accelerated flowering.

Geranium 'Sooner Red' grown under ambient light initiated flowers 37 days earlier and differentiation time was reduced by 7 days compared to plants grown under 60% shade (Armitage and Wetzstein, 1984). Shade-grown plants had 22-24 nodes at flower initiation compared with 16-18 under ambient light (Armitage and Wetzstein, 1984). There was a 1-2 °C difference in plant temperature on a clear day between the shaded and ambient part of the greenhouse bench, so the delays observed under the shade may have been affected by slightly lower temperatures. Higher light intensities

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decreased the juvenile period by decreasing time from sowing to flower initiation as well as time for floral organ differentiation (Armitage and Wetzstein, 1984).

Benefits of supplemental lighting have also been observed in stock (Matthiola incana L.). At 18 °C DT/14 °C NT, plants under an additional 60 µmol·m⁻²·s⁻¹ from HPS lighting (16-h day) flowered 20-25 days earlier compared with plants under ambient light conditions (Dansereau et al., 1998). Begonia semperflorens plugs 'Pizzazz Red', 'Vodka', and 'Viva' days from sowing to visible bud were reduced by \approx 14 days, \approx 19 days, and \approx 15 days for each cultivar, respectively, when exposed to 125 μ mol·m⁻²·s⁻¹ supplemental metal halide light in comparison with treatments of 50 and 200 µmol·m⁻²·s⁻¹ (at 18 °C NT and a DT that did not exceed 29 °C) (Kessler et al., 1990). There were no significant differences between 50 and 200 μ mol·m⁻²·s⁻¹ (Kessler et al., 1990). This may indicate a threshold light level for *Begonia*, which is often considered a shade tolerant plant. In petunia, a DLI of 13 rather than 6.6 mol \cdot m⁻²·d⁻¹ decreased time to flower by up to 3 weeks (Kaczperski et al., 1991). However in campanula 'Blue Clips', increasing DLI from 4.2 to 15.8 mol \cdot m⁻²·d⁻¹ did not have an effect on time to flower when grown at temperatures ranging from 15 to 25 °C (Niu et al., 2001).

Plant Quality and DLI

Plant quality is greatly affected by the total amount of irradiance a plant receives. In general, the greater the DLI, the higher quality the plant. Some measures of quality affected by DLI are plant height, branching, dry weight, flower size and flower number.

Plant Height

Plant height can also be affected by DLI, often with increases in DLI leading to decreases in height. In geranium 'Sprinter Scarlet', 'Sprinter White', and 'Ringo', total and vegetative plant height were correlated to DLI (Erickson et al., 1980). Significant differences in vegetative and total height were observed between 4, 6, 9, 10, and 12 mol \cdot m⁻²·d⁻¹ for each cultivar; as DLI increased, height decreased (Erickson et al., 1980). Branching

In geranium 'Sprinter Scarlet', 'Sprinter White', and 'Ringo', the number of lateral breaks increased from ≈ 1 to ≈ 4 as cumulative PAR increased from 4 to 12 mol·m⁻²·d⁻¹ (Erickson et al., 1980). In *Begonia* 'Rosalie' and 'Schwabenland', the number of side shoots per plant was greater (by 2.5 and 2, respectively) with supplemental HPS lighting ($\approx 32 \mu \text{mol·m}^{-2} \cdot \text{s}^{-1}$ additional for 16-h) compared to plants grown under ambient light alone (Vogelzang and Veberkt, 1990). However, these significant differences were only observed when plants were grown in November (when ambient light levels were lower) as opposed to those grown beginning in February (Vogelzang and Veberkt, 1990).

Dry Weight

For ornamental plants, the most useful measure of the efficiency of higher plant growth is grams of total biomass per mol of photosynthetic photons (Moe, 1997). In general, as DLI increases, dry weight increases, although the rate of dry weight increases at a decreasing rate.

DLI had a positive linear effect on increasing seedling dry weight accumulation 43 days post emergence in *Petunia* ×*hybrida* 'Red Flash'; there was a 10% increase in dry weight between plants sown in February to those grown in March, hence under higher light intensities later in the spring. (Graper et al., 1990). In a separate study, Graper and Healy (1992) investigated *Petunia* ×*hybrida* 'Red Flash' seedlings and found that doubling DLI from 10 to 20 mol·m⁻²·d⁻¹ increased total carbohydrate production by 60%, seedling dry weight by 30%, and rate of seedling growth by 25%.

There was over a 50% increase in *Begonia semperflorens* Link & Otto. 'Pizzazz Red', 'Vodka', and 'Viva' seedling dry weight after 8 weeks under a supplemental lighting treatment of 125 μ mol·m⁻²·s⁻¹ provided by metal halide lamps, compared with plants under 0, 50, or 200 μ mol·m⁻²·s⁻¹ (16-h days) (Kessler et al., 1990). In a study on foliage plants, supplemental HPS lighting (~44 μ mol·m⁻²·s⁻¹ for a 16-h day) increased dry weight by 146% in *Hedera* sp. L. 'Variegata', 82% in *Fatshedera* sp. Guill. 'Pia', 93% in *Codiaeum* sp. A. Juss. 'Gold Sun', and 100% in *Ficus* sp. L. 'Starlight', when grown at 22 °C DT/ 20 °C NT as compared with ambient light levels (Vogelezang and Verberkt, 1990).

Flower Size and Number

Flower size and number generally increase as DLI increases. Flowers of shade grown geranium 'Sooner Red' were smaller and fewer in number, compared with ambient grown plants, both during differentiation and at anthesis (Armitage and Wetzstein, 1984). In *Campanula* 'Deep Blue Clips', flower size and number were similar when grown under DLIs ranging from 5 to 17 mol·m⁻²·d⁻¹ before visible bud

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(Niu et al., 2001). Supplemental lighting after visible bud partially compensated for smaller flower number under higher temperatures; the number of flower buds was $\approx 40\%$ higher under 17 mol·m⁻²·d⁻¹ after visible bud at 22 to 24 °C than under 5.7 mol·m⁻²·d⁻¹ at 14 to 16 °C (Niu et al., 2001). Flower size also increased as DLI increased; at temperatures ranging from 14 to 26 °C, flowers were $\approx 10-15\%$ larger under 17 mol·m⁻²·d⁻¹ than under 5 mol·m⁻²·d⁻¹ (Niu et al., 2001). In vinca 'Grape Cooler' increased flower size (15-20%) was observed under a DLI of ≈ 29 mol·m⁻²·d⁻¹ in comparison with plants under ambient (≈ 18 mol·m⁻²·d⁻¹) and under 50% shade cloth (≈ 9 mol·m⁻²·d⁻¹) across temperatures ranging from 15 to 35 °C (Pietsch et al., 1995).

Interaction of Temperature and Light Intensity

Floral Development Rate

Rate of flower development can be affected by temperature and light intensity. Temperatures of 13 °C versus 17 °C delayed flowering by two weeks with Geranium 'Fire Flash', 'Encounter Red' and 'Sprinter Salmon' (Tsujita, 1982). Although no statistical interaction between light and temperature was found, supplementary HPS irradiation for 6 or 8 weeks overcame the delay in flowering induced by low night temperature. Six or eight weeks of supplemental HPS lighting accelerated flowering of 'Fire Flash' by 8 or 13 days, respectively, at 17 °C and 'Sprinter Salmon' by 14 or 17 days, respectively, at 17 °C (Tsujita, 1982). Four weeks of supplemental HPS lighting accelerated flowering of 'Encounter Red', by approximately 11 days (Tsujita, 1982). There were no plant temperatures reported in this study, so the 6 or 8 weeks of the HPS lighting could have increased plant temperature, and thus partially explain the earlier

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flowering. Studies on vinca (*Catharanthus roseus* L.) showed that shoot tip temperature can be greater than air temperature (Faust and Heins, 1997). Shoots receiving supplemental HPS lighting of 50, 75, and 100 μ mol·m⁻²·s⁻¹ were 1.2, 1.5, and 1.7 °C higher, respectively, than that of plants in the dark (Faust and Heins, 1997). However, in a similar study, no statistically significant interactions between temperature and light intensity were reflected in growth and development of geranium 'Red Elite' when leaf temperatures were used (White and Warrington, 1984).

In petunia 'Snow Cloud', plants flowered in 67 days when grown at 20 °C and under 6.5 mol·m⁻²·d⁻¹; however, when the light intensity was doubled, the plants flowered in 56 days (Kaczperski et al., 1991). In this study, it was shown that the average temperature could be lowered to 15 °C and plants would still flower at the same time as those grown at 20 °C at the lower irradiance (Kaczperski et al., 1991).

Different phases of development may be influenced differently by temperature and light intensity. In 1999, Adams et al. studied the effects of temperature and light intensity on the different phases of photoperiod sensitivity in petunia 'Express Blush Pink.' They showed that the length of the photoperiod-insensitive juvenile phase of development was sensitive to light integral and temperature. Low light integrals prolonged the phase from 23 days under 5.1 mol·m⁻²·d⁻¹ to 36 days under 3.1 mol·m⁻²·d⁻¹ . The length of this phase was shortest (13 days) at 21 °C, and longer at 13.5 °C and 28 °C (21 and 18 days, respectively). After this phase, time to flowering was primarily influenced by photoperiod, with long days (16-h) hastening flowering between 28 and 137 days, as compared with short days depending on the temperature. The duration of the final phase of development was dependent primarily on temperature; at 14.5 °C, it took 34 days to complete this phase and at 25.5 °C it took 11 days.

Another example of different influences of temperature and light intensity during different developmental phases occurred with geranium 'Sooner Red'. Time from seed to visible bud was negatively correlated to quantum flux density at a given temperature; however, the time from visible bud to flowering was negatively correlated with temperature, while light had no effect (Armitage et al., 1981).

In 1997, a study on the quantitative long day plant pansy 'Universal Violet' by Adams et al. showed that temperature, DLI, and photoperiod each had independent linear effects on the rate of progress to flowering, without any interaction. Interestingly, the estimated optimum temperature for time to flower decreased linearly from ≈ 21 °C to ≈ 16 °C as DLI decreased from ≈ 6.7 mol·m⁻²·d⁻¹ to ≈ 4 mol·m⁻²·d⁻¹.

Height and Shoot number

Plant height at flowering of petunia 'Snow Cloud' increased as day temperature increased from 10 °C to 30 °C (Kaczperski et al., 1991). Plant height was influenced more by low irradiance (6.5 mol·m⁻²·d⁻¹) at warmer temperatures than cooler temperatures; plants were 20% shorter at 30 °C and only 4% shorter at 10 °C under 6.5 mol·m⁻²·d⁻¹ as compared to those grown under 13 mol·m⁻²·d⁻¹ (Kaczperski et al., 1991).

Temperature significantly affected plant height at flowering of geranium 'Encounter Red' under all light treatments. Plants grown at 13 °C NT were shorter (7-10%) and had a larger number of shoots (20-130%) than plants grown with a 17 °C NT

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(Tsujita, 1982). 'Sprinter Salmon' and 'Fire Flash' lighted for 8 weeks were 10 and 14% shorter, respectively, at 13 °C than at 17 °C (Tsujita, 1982).

In *Impatiens* 'Accent Red', linear regression coefficients of shoot height as a function of plug medium temperature were 67 to 172% higher for seedlings grown under 24-h continuous lighting of $\approx 215 \ \mu mol \cdot m^{-2} \cdot s^{-1}$ as compared with those grown under $\approx 335 \ \mu mol \cdot m^{-2} \cdot d^{-1}$ in a growth chamber (Dressen and Langhans, 1992). The predicted height of seedlings grown at a lower light level at a plug medium temperature of 20, 22.5, and 25 °C are 2%, 7%, and 18% greater, respectively, than those for high light seedlings at the same temperature (Dressen and Langhans, 1992).

Plant mass

Plant mass can be affected by both temperature and light. One model developed for petunia 'Snow Cloud', indicated that the optimum temperature for shoot dry weight gain shifts from 14.6 °C at 5 mol·m⁻²·d⁻¹ to 33.5 °C at 30 mol·m⁻²·d⁻¹(Lieth et al.,1990). A separate study on pansy 'Universal Violet' indicated that dry matter accumulation was primarily a function of temperature and DLI (Adams et al., 1997). Shoot dry weight was greatest at temperatures of ≈ 20 °C and dry matter accumulation was reduced at both warmer and cooler temperatures. Additionally, relative growth rate increased linearly with DLIs up to ≈ 20 mol·m⁻²·d⁻¹ (Adams et al., 1997). This model presented for pansy 'Universal Violet' did not predict an optimum temperature shift with changes in DLI, but the authors suggest that this may be a potential deficiency in the model and may account for some unexplained variance (Adams et al., 1997).
seedlin produc irradia 20 day 1990). Supple 120 μr develo Ambie ²·s⁻¹ lig indicate subsequ 167 μm for 14 c weight) for up t treatmen 4 ^{also} bee Seedling Some studies have been performed on the effects of temperature and DLI on seedling dry weight, as this is an important factor of growth and quality in plug production. In *Petunia* ×*hybrida* 'Red Flash', the critical period for supplemental irradiation to obtain an optimum increase in seedling dry weight was 10-15 days or 10-20 days after germination with supplemental root zone heating to 27 °C (Graper et al., 1990). Providing light before or after this period was 30% less effective. Supplemental root zone heating to 27 °C combined with additional 24-h HPS lighting of 120 μ mol·m⁻²·s⁻¹ increased rates of seedling development. Part of the increase in development was due to increased soil temperature under higher light intensities. Ambient soil temperatures ranged from 17.5 °C to 21.1 °C under the 13 to 233 μ mol·m⁻²·s⁻¹ lighting treatments, up to a 4 °C difference (Graper et al., 1990). Additionally, indicate that as the spring season progressed from January to March and DLI increased, subsequent time to flower decreased by up to 14 days (Graper et al., 1990).

In a separate study on *Petunia* ×*hybrida* 'Red Flash', providing an additional 167 μ mol·m⁻²·s⁻¹ from HPS lighting (24-h) and increasing plant temperature by 4.3 °C for 14 days following seedling emergence increased relative growth rate (based on fresh weight) by 45% (Graper and Healy, 1991). The increased growth rate was observed for up to seven days after treatment, but was not sustained after removal from the treatment (Graper and Healy, 1991).

A synergistic effect between supplemental irradiance and root zone heating has also been reported for *Begonia semperflorens* 'Vodka' (Graper and Healy, 1990). Seedling dry weight accumulation, 43 days post emergence, increased (linearly and

quadratically) with increasing supplemental HPS irradiance (ranging from 13 to 233 μ mol·m⁻²·s⁻¹ for 24-h) provided 15 through 25 days after emergence (Graper and Healy, 1990). At ambient soil temperatures, seedling dry weight increased by 25% as supplemental irradiance increased from 13 to 233 μ mol·m⁻²·s⁻¹. The addition of root zone heating to the increase in irradiance increased dry weight by 33% (Graper and Healy, 1990). As an additional benefit, as the initial supplemental light increased from 13 to 233 μ mol·m⁻²·s⁻¹ (applied days 15-25 post emergence), days to transplant and days to flower decreased by ≈5 days (Graper and Healy, 1990). This decrease in days to flower may have been partially influenced by increased temperature under higher light intensities, but plant temperature was not reported.

Impatiens 'Accent Red' (10 to 25 days old) were also studied to determine the effects of 24-h supplemental lighting (\approx 215 to \approx 335 µmol·m⁻²·s⁻¹) and temperature (18-29 °C) on seedling dry weight in growth chambers (Dressen and Langhans, 1992). Shoot dry weight was linearly related to plug medium temperature at all irradiance levels studied, except for those under the highest light intensity (\approx 335 µmol·m⁻²·s⁻¹). At high irradiance levels, shoot dry weight decreased at plug medium temperatures >25 °C. At lower light levels, shoot dry weight continued to increase with all temperatures studied (Dressen and Langhans, 1992). The maximum relative growth rate was predicted to occur 12 days from sowing at 19.6 °C, 11 days at 21.6 °C, and 10 days at 23.6 °C. Cooler temperatures delayed the occurrence of the highest relative growth rates (Dressen and Langhans, 1992).

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Leaf Unfolding Rate

The combined effect of DLI and temperature on vegetative development rates has not been determined on the vast majority of herbaceous plants. One example with African violet (*Saintpaulia ionantha* Wendl. 'Utah') showed that maximum leaf unfolding rate was 0.27 leaves d⁻¹, which occurred at 25 °C and with 10 mol·m⁻²·d⁻¹ (Faust and Heins, 1993). However, the optimum air temperature for leaf unfolding decreased to 23 °C and the maximum rate decreased to 0.18 leaves d⁻¹a s the DLI decreased from 10 to 1 mol·m⁻²·d⁻¹ (Faust and Heins, 1993). In a separate study, leafunfolding rate was linearly related to mean temperature and DLI in pansy 'Universal Violet' (Table 1) (Adams et al., 1997).

Photothermal ratio

Recently, the concept of combining the effects of thermal energy and radiant energy into a photothermal ratio (PTR) has been investigated in poinsettia 'Freedom' (Liu and Heins, 2002). PTR is a ratio of mean DLI ($mol \cdot m^{-2} \cdot d^{-1}$) to mean temperature (°C) above a base temperature, and the units for this measurement are mol/degree-day per plant. The effects of PTR during the vegetative stage (PTR^{*}) and during the reproductive stage (PTR^r) on plant quality in poinsettia 'Freedom' were investigated (Liu and Heins, 2002).

Both PTR' and PTR' affected final plant dry weight. Total, leaf, stem, and bract dry weight increased linearly as PTR' increased and responded quadratically and reached a maximum when PTR' was 0.04 mol/degree-day per plant. When PTR' increased from 0.02 to 0.06 mol/degree day per plant, stem diameter increased by

≈24% linear diame PTR' demo demo growt correla et al., increas mol/de above $\approx 24\%$, while stem strength increased 75%. The size of bracts and cyathia increased linearly as PTR' increased, but was unaffected by PTR'. Bract area, inflorescence diameter, and cyathia diameter increased 45%, 23%, and 44%, respectively, when PTR' increased from 0.02 to 0.06 mol/degree-day per plant. This experiment not only demonstrates the combined effects of thermal and light energy on plant quality, but also demonstrates that the effects differ between stages of vegetative and reproductive growth and development.

In *Campanula carpatica* 'Blue Clips,' flower bud number and dry mass were correlated closely to PTR, while flower size was only weakly correlated with PTR (Niu et al., 2001). Flower bud number increased (from ≈ 25 to ≈ 200) and dry mass increased (from ≈ 1 to ≈ 6 g/plant) linearly as PTR increased from 0.2 to 1.0 mol/degree-day. However, flower size was more closely related to temperature; DLIs above 10 mol·m⁻²·d⁻¹ did not increase flower size.

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SECTION II

The Effects of Temperature and Daily Light Integral on Bedding Plant Plug Growth and

Development

The Effects of Temperature and Daily Light Integral on Bedding Plant Plug Growth and Development

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Additional index words: Celosia, Impatiens, Saliva, Tagetes

Received for publication ______. Accepted for publication ______. We gratefully acknowledge funding from growers providing support for Michigan State University floriculture research and support from the Michigan Agriculture Experiment Station.

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Introduction

The production of bedding plants in northern climates forces bedding plant plug growers to rely on heating in the winter and early spring. Additionally, some growers use supplemental lighting because of naturally low light levels. In response to increasing energy costs, growers may change temperature set points or lighting strategies to reduce short-term fuel costs, but crop timing and quality may be compromised in the process. Crop timing during the plug stage is of great importance due to specific market dates. Quality factors, such as compactness and strong, thick stems are important during shipping and for ease of transplant.

Temperature and daily light integral (DLI) are known to affect plant growth and development, and studies on this interaction have been performed in some species such as petunia (*Petunia* ×hybrida Hort. Vilm.-Andr.), pansy (*Viola* ×wittrockiana Gams.), vinca (*Catharanthus roseus* L.), and geranium (*Pelargonium* ×hortorum Bailey) (Adams et al., 1997; 1999; Armitage et al., 1981; Pietsch et al., 1995). However, these studies mainly focus on the finish stages of plant and flower development. With the advent of plug technology comes a need to understand how these factors affect plant growth and development specifically during the seedling stage.

Some studies have been performed on seedlings to determine the relationship between dry weight, a main indicator of growth and quality in plugs, and the interaction between temperature and supplemental lighting. In *Begonia semperflorens* seedlings, supplemental irradiance and root zone heating had a synergistic effect in dry weight

accumulation (Graper and Healy, 1990). At ambient soil temperature, seedling dry weight increased by 25% as the irradiance increased from 13 to 233 μ mol·m⁻²·s⁻¹. The addition of root zone heating and the increase in irradiance increased dry weight by 33% (Graper and Healy, 1990). In *Petunia* ×hybrida, supplemental root zone heating to 27 °C combined with additional 24-h HPS lighting of 120 µmol·m⁻²·s⁻¹ increased rates of seedling development (Graper et al., 1990). However, part of the increase in development was due to increased soil temperature under the higher light intensities; the difference between plants under the 13 to 233 μ mol m² s⁻¹ lighting treatments varied by up to 4 °C (Graper et al., 1990). In a separate study on *Petunia* ×hybrida, providing an additional 167 µmol·m⁻²·s⁻¹ HPS lighting (24-h) and increasing plant temperature by 4.3 °C for 14 days following emergence increased seedling relative growth rate (based on fresh weight) by 45% (Graper and Healy, 1991). Seedling shoot dry weight of Impatiens 'Accent Red' (10 to 25-day old) was linearly related to plug medium temperature (18-29 °C) under all irradiance levels (≈ 215 to ≈ 335 µmol·m⁻²·s⁻¹), except for those under the highest light intensity (Dressen and Langhans, 1992). At high irradiance levels, shoot dry weight decreased when plug medium temperature was greater than 25 °C.

Although these studies provide information on the interaction of temperature and light on some species during the seedling stage, more research in this area is warranted due to the variability of optimum temperatures and light requirements among species and between growth and developmental processes.

This research was designed to determine how temperature and DLI influence growth and quality of four popular bedding plant species at the seedling (plug) stage: *Celosia argentea* var. *plumosa* 'Gloria Mix', *Impatiens wallerana* 'Accent Red', *Salvia splendens* 'Vista Red', and *Tagetes patula* 'Bonanza Yellow'.

Materials and Methods

Seeds of *Tagetes patula* 'Bonanza Yellow', *Impatiens wallerana* 'Accent Red', *Celosia argentea* var. *plumosa* 'Gloria Mix', and *Salvia splendens* 'Vista Red' were sown in 288-cell plug trays on 4 January 2002 and 2 April 2002 at a wholesale plug producer (Raker's Acres, Litchfield, MI). Plants were received at Michigan State University on 10 January 2002 and 8 April 2002. Plugs were placed on capillary mats and were top irrigated with well water (containing 95, 34, and 29 mg·L⁻¹ Ca, Mg, and S, respectively) supplemented with a water soluble fertilizer to provide the following (mg·L⁻¹): 40 N, 4 P, 40 K, 5 Ca, 0.3 Fe, 0.03 B and Mo, and 0.2 Mn, Zn, Cu (MSU Special; Greencare Fertilizers, Chicago, IL). The water was acidified with H₂SO₄ to a titratable alkalinity of ~140 mg·L⁻¹ CaCO₃.

The plug trays were split in half, thinned to one seedling per cell, and randomly placed in treatments in 5 glass glazed greenhouse compartments set at constant 14, 17, 20, 23, and 26 °C. Greenhouse air temperature was measured by an aspirated thermocouple and soil temperatures were measured by a thermocouple placed just under the soil surface under ambient light treatments. Average air temperatures were used for analysis. Within each compartment, two half trays were placed under one of three light environments, ambient light plus 50% shade cloth (OLS 50; Ludvig Svensson,

Charlotte, NC), ambient light, and ambient plus supplemental high-pressure sodium (HPS) lighting ($\approx 170 \ \mu mol \cdot m^{-2} \cdot s^{-1}$). Plants in all treatments were exposed to a 16-h photoperiod, from 700 HR to 2200 HR, using HPS lamps which delivered ≈ 34 , ≈ 75 , $\approx 170 \ \mu mol \cdot m^{-2} \cdot s$ under the ambient light plus 50% shade cloth, ambient light, and ambient plus supplemental high-pressure sodium, respectively. Line quantum sensors (Apogee Instruments, Inc. Logan, Utah) were placed under the three lighting treatments in three of the five greenhouse compartments to measure photosynthetic photon flux (PPF). Instantaneous values were converted to DLIs, which were used for analysis. Vapor pressure deficit was maintained at ≈ 0.7 kPa by steam injection. A CR10 data logger (Campbell Scientific, Logan, Utah) recorded the environmental data every 10 seconds and hourly averages were reported (Table 1 and 2).

Plant height, node number, and shoot dry weight were recorded when plugs in each light and temperature treatment were considered ready for transplant. *Tagetes* plugs were considered ready for transplant when the second set of leaves reached 4.5 cm across; *Celosia*, when seedlings were at least at the fourth leaf stage and were 4.5 cm across; *Salvia*, when the second leaf pair was 3.5 cm across; and *Impatiens*, when the sixth leaf was 1 mm in length. Ten plants per half tray were measured, totaling 20 plugs per treatment per replication. Data were not recorded from the outer 2 rows of plants, as to decrease edge effects. Date of visible bud was recorded if present at time of transplant.

Average temperature and DLI were calculated for each treatment and regression analysis was performed using SAS (SAS Institute Inc., Cary, NC) response surface

regression (RSREG procedure). If the contribution of individual terms to the model were not significant, the terms were removed, and regression (REG procedure) was used to determine the model coefficients. Individual terms were included if P < 0.05. Results

Celosia. Time to finish was significantly affected by temperature and DLI. Plugs finished the earliest (in 20 days) when grown at 28 °C and under 24 mol \cdot m⁻²·d⁻¹ (Fig. 1). Increasing DLI decreased time to finish linearly at all temperatures. especially at the lower temperatures. At 14 °C and under a DLI ranging from 4 to 17 mol·m⁻²·d⁻¹, Celosia showed severe chlorosis and did not reach the finish stage within 60 days, when the experiment ended, so data were not included in any of the models. Predicted base temperature was 12.4 °C under 10 mol·m⁻²·d⁻¹. Dry weight increased linearly at all temperatures as DLI increased and was quadratically related to temperature at all DLIs, reaching a maximum at 23 °C under 24 mol·m⁻²·d⁻¹ (Fig. 2). Seedling height was significantly affected by temperature and DLI, but data were highly variable ($\mathbb{R}^2 = 0.17$) (Fig. 3). Under 4 mol·m⁻²·d⁻¹, plant height increased with temperature. At the lowest temperatures studied (16 °C), plant height increased with DLI. Node number increased from 6 to 12 as temperature decreased from 27 °C to 16 °C and DLI increased from 4 to 24 mol \cdot m⁻²·d⁻¹ (Fig. 4). The greatest percentage of visible flower bud (70%) at the time of finish was observed at 17 °C and under 16 $mol \cdot m^{-2} \cdot d^{-1}$, while no buds were present when plugs were grown at 24 to 28 °C under all light intensities (Fig. 5).

Impatiens. Time to finish was significantly affected by temperature and DLI. Fastest time to finish was 28 days at 27 °C and under 23 mol·m⁻²·d⁻¹, and was 35 days earlier than plugs grown at 14 °C receiving 4 mol·m⁻²·d⁻¹. Fig. 6 is the response surface developed from the observed data. Predicted base temperature was 7.3 °C under 10 mol·m⁻²·d⁻¹. Impatiens dry weight was greatest at 14 °C and under 26 mol·m⁻²·d⁻¹ (Fig. 7). Impatiens had the least biomass and were tallest at the highest temperature and lowest DLI (26 °C and 4 mol·m⁻²·d⁻¹) (Fig. 7 and 8). Plugs averaged between 5 to 8 leaves at finish (Fig. 9). Impatiens had high percentages of visible flower bud when grown under most temperature and DLI treatments; only those grown at \geq 27 °C did not have flower buds at the time of finish (Fig. 10).

Salvia. Time to finished plug was significantly affected by temperature, but not by DLI. Time to finish decreased by 20 days as temperature increased from 14 to 28 °C (Fig. 11). Predicted base temperature was 3 °C. Dry weight was significantly affected by both temperature and DLI, and was greatest at 14 °C under 24 mol·m⁻²·d⁻¹ and lowest at 26 °C and with 4 mol·m⁻²·d⁻¹ of light (decreasing by \approx 70%) (Fig. 12). Plugs were tallest at 28 °C and 4 mol·m⁻²·d⁻¹ and were shortest under 14 °C and 4 mol·m⁻²·d⁻¹ (decreasing by \approx 60%) (Fig. 13). At finish, all plugs under all treatments had an average of 3 to 4 nodes (Fig. 14). Only plugs grown at 16 and 20 °C under the highest DLI (\geq 19 mol·m⁻²·d⁻¹) had visible flower buds at the time of finish (Fig. 15).

Tagetes. Temperature had a significant effect on days to finish, whereas DLI did not. Days to finish decreased by ≈ 12 days as temperature increased from 14 to 28 °C (Fig. 16). Predicted base temperature was -10.3 °C. Dry weight increased as DLI

increased at all temperatures, but DLI had the greatest effect at the coolest temperatures (Fig. 17). Marigold height increased by 43% as temperature increased from 14 to 28 $^{\circ}$ C under 4 mol·m⁻²·d⁻¹ and by 15% under 26 mol·m⁻²·d⁻¹ (Fig. 18). Plugs under all treatments had 3 or 4 leaf pairs at finish (Fig. 19). Plugs had the lowest visible bud percentage when grown warm (24 to 28 °C) and under the lowest DLIs (Fig. 20). At least 60% were reproductive when grown at all other temperature and DLI combinations.

Discussion

Temperature influenced days to finish in all species, while DLI had a significant effect on development time only in *Celosia* and *Impatiens*. Some of the effect attributed to DLI may have been due to higher plant temperatures under the HPS lamps. For example, it has been shown that the temperature of vinca shoots receiving supplemental HPS lighting of 50, 75, and 100 μ mol·m⁻²·s⁻¹ was 1.2, 1.5, and 1.7 °C higher, respectively, than that of plants in the dark (Faust and Heins, 1997).

Dry weight is an overall measure of the size and vigor of a plant. For plug production, dry weight is important because strong plants are needed for transplanting, especially with mechanized transplanting systems. Increasing DLI and temperature have been found to increase dry weight of plugs in similar studies. *Begonia semperflorens* dry weight (at 40 days post seedling emergence) increased as supplemental irradiance increased from 13 to 233 μ mol·m⁻²·s⁻¹ (24-h), and was further increased by root zone heating to 27 °C (Graper and Healy, 1990). In petunias, increasing ambient light intensity by 53% and elevating plant temperatures by 4.3 °C increased seedling relative growth rate (In fresh weight) by 45% (Graper and Healy, 1991). Our studies show similar results, as dry weight at finish was significantly affected by temperature and DLI in all species studied (Fig. 2, 7, 11, 15). The largest increases in dry weight due to DLI were observed under the cooler air temperatures where growth and development were slower. Thus, the plants had a longer duration of time to harvest light. In *Impatiens*, dry weight generally increased with decreasing temperature, although, when temperature was >20 °C, plant dry weight did not increase as the DLI increased above $\approx 14 \text{ mol m}^{-2} \text{ d}^{-1}$. In *Celosia, Salvia,* and *Tagetes,* increasing daily light integral increased plant dry weight at all temperatures provided in treatments. Additionally, growing *Salvia, Tagetes,* and *Impatiens* under increasingly cooler temperatures from 26 to 14 °C increased dry weight (and thus improved quality and strength of the plugs). However, this strategy of increasing plug quality also increases time to reach a mature plug.

Height is an important quality factor for plugs, as it is desirable to have compact plugs for shipping, transplanting, and aesthetic purposes. At high DLIs as temperature increased, height of *Tagetes, Salvia, and Impatiens* increased, although height decreased in Celosia. At low DLIs, height increased with increasing temperatures in the species studied.

Celosia height was highly variable, but the response curve showed a similar response under higher temperatures to *Salvia* and *Impatiens*. However, at lower temperatures, increasing DLI had a much more dramatic affect on increasing plant height, which could be explained by more nodes developing before plants reached

finish stage. *Celosia* leaves were smaller and chlorotic under the cooler temperatures, so they did not reach the specified 4.5 cm plant width until they had developed several more nodes. Thus, a better developmental point to determine *Celosia* as "finished" would have been more appropriate in this study.

Early flower initiation, such as during the seedling plug stage, can decrease time to flower in subsequent growth environments. High percentages of visible flower bud were observed at the finish plug stage in *Tagetes* and *Impatiens* in most temperature and DLI combinations. In contrast, *Salvia* and *Celosia* had very low percentages at the time of finish. For all species studied, however, visible bud percentage was greatest when plugs were grown under the highest DLIs and coolest temperatures. Reproductive seedlings will reach flowering earlier than seedlings that are vegetative, which can be desirable for greenhouse growers who want rapid flowering in a finish container. However, this may not be beneficial in cases where more vegetative growth is desired before flowering occurs, such as when seedlings are transplanted into large finish containers.

Responses to temperature and DLI are truly unique to each bedding plant species, although some trends among species can be observed. This information will enable bedding plant growers to better predict the timing of their plugs, which is extremely important due to large volumes of plugs produced in short periods of time, when heating is expensive, and natural light intensities are increasing in the months of January through April. Additionally, this information will allow growers to better predict quality of plugs at finish when grown under a wide range of greenhouse temperature and DLI combinations.

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Replication	Average soil temperature (°C) (Under ambient conditions)			il temperature (°C) Average air temperature (°C) abient conditions)						
	14	17	20	23	26	14	17	20	23	26
1	14.4	17.4	19.2	24.0	26.0	14.5	16.7	20.2	23.7	26.3
2	17.0	18.4	19.9	24.5	26.7	16.6	17.6	20.6	25.4	27.3

Table 1. Actual temperature recorded in greenhouse sections.

Table 2. Actual daily light integral (DLI) recorded in greenhouse sections.

Replication	Treatment	Average DLI $(mol \cdot m^{-2} \cdot d^{-1})$
1	Ambient light plus 50% shade cloth	4.1
	Ambient	8.6
	Ambient plus HPS	15.5
2	Ambient light plus 50% shade cloth	10.8
	Ambient	19.4
	Ambient plus HPS	24.1

	Days to finish	Dry weight	Height	Node number				
	Celosia							
Т	***2	***	***	***				
DLI	***	***	***	***				
T*DLI	*	***	***	*				
		Impatiens						
Т	***	***	***	***				
DLI	***	***	***	***				
T*DLI	***	NS	***	***				
	Salvia							
Т	***	***	***	***				
DLI	NS	***	***	***				
T*DLI	NS	***	***	***				
	Tagetes							
Т	***	***	***	***				
DLI	NS	***	***	***				
T*DLI	NS	***	**	NS				

Table 3. Significance of temperature (T), daily light integral (DLI), and their interaction (T*DLI) to the models developed for *Celosia*, *Impatiens*, *Salvia*, and *Tagetes* at finish.

²NS, *, **, *** Nonsignificant or significant at $P \le 0.05$, 0.01, 0.001, respectively.



Figure 1. Response surface for *Celosia* days to finish as a function of average daily temperature (T) and average daily light integral (DLI). Celosia was considered to be finished when the plug was at the fourth leaf stage and reached 3.5 cm in width. The equation for the response surface was y = 111.901 - 3.25716T - 1.41259DLI + 0.04514T*DLI with $R^2 = 0.96$.



Figure 2. Response surface for *Celosia* dry weight as a function of average daily temperature (T) and average daily light integral (DLI). The equation for the response surface was $y = -0.19702 + 0.01817T + 0.00749DLI - 0.00037254T^2 - 0.00023343T*DLI$ with R² = 0.54.



Figure 3. Response surface for *Celosia* height as a function of average daily temperature (T) and average daily light integral (DLI). The equation for the response surface was $y = 2.50443 + 0.13542DLI + 0.00342T^2 + 0.00223DLI - 0.00951T*DLI$ with $R^2 = 0.17$.



Figure 4. Response surface for *Celosia* node number at finish as a function of average daily temperature (T) and average daily light integral (DLI). The equation for the response surface was $y = 29.329 - 1.75315T + 0.25702DLI + 0.03216T^2 - 0.00865T*DLI$ with $R^2 = 0.65$.



Figure 5. The influence of temperature and daily light integral (DLI) on visible bud percentage at the finish plug stage in *Celosia*.



Figure 6. Response surface for *Impatiens* days to finish as a function of average daily temperature (T) and average daily light integral (DLI). The equation for the response surface was $y = 185.41233 - 11.27041T - 1.53677DLI + 0.20366T^2 + 0.05670T*DLI$ with $R^2 = 0.96$.



Figure 7. Response surface for *Impatiens* dry weight at finish as a function of average daily temperature (T) and average daily light integral (DLI). The equation for the response surface was $y = 0.10154 - 0.00651T + 0.00245DLI + 0.0001202T^{2}$ - 0.00005133DLI² with R² = 0.39



Figure 8. Response surface for *Impatiens* height at finish as a function of average daily temperature (T) and average daily light integral (DLI). The equation for the response surface was $y = 5.896504 - 0.421892T + 0.065601DLI + 0.014178T^{2}$ + 0.002082DLI² - 0.007713T*DLI with R² = 0.39.



Figure 9. Response surface for *Impatiens* node number at finish as a function of average daily temperature (T) and average daily light integral (DLI). The equation for the response surface was $y = -4.54 + 0.82677T + 0.24486DLI - 0.01542T^2 - 0.00786T*DLI$ with R² = 0.31.



Figure 10. The influence of average daily temperature (T) and average daily light integral (DLI) on visible bud percentage at finish in *Impatiens*.


Figure 11. The influence of temperature on days to finished plug in *Salvia*. Daily light integral (DLI) did not have a significant effect on days to finished plug. Plugs were considered finished when the second leaf pair reached 3.5 cm in width.



Figure 12. Response surface for *Salvia* dry weight at finish as a function of average daily temperature (T) and average daily light integral (DLI). The equation for the response surface was y = 0.057617 - 0.004011T + 0.004607DLI + 0.000095013 $T^2 - 0.000026618DLI^2 - 0.000108T*DLI$ with $R^2 = 0.60$.



Figure 13. Response surface for *Salvia* height at finish as a function of average daily temperature (T) and average daily light integral (DLI). The equation for the response surface was $y = 1.761064 - 0.081501T + 0.158651DLI + 0.009023T^{2}$ + 0.002123DLI² - 0.012233T*DLI with R² = 0.55.



Figure 14. Response surface for *Salvia* node number at finish as a function of average daily temperature (T) and average daily light integral (DLI). The equation for the response surface was $y = 6.85962 - 0.30447T + 0.00538T^2 - 0.00095188DLI^2 + 0.00332T*DLI$ with $R^2 = 0.39$.



Figure 15. The influence of temperature and daily light integral (DLI) on visible bud percentage at the finish plug stage in*Salvia*.



Figure 16. The influence of temperature on days to finished plug in *Tagetes*. Daily light integral (DLI) did not have a significant effect on days to finished plug. Plugs were considered finished when the second leaf pair reached 4.5 cm in width.



Figure 17. Response surface for *Tagetes* dry weight at finish as a function of average daily temperature (T) and average daily light integral (DLI). The equation for the response surface was y = 0.05653 - 0.00460T + 0.00587DLI + 0.00011621 $T^2 - 0.00017692T*DLI$ with $R^2 = 0.60$.



Figure 18. Response surface for *Tagetes* height at finish as a function of average daily temperature (T) and average daily light integral (DLI). The equation for the response surface was $y = 4.85607 - 0.21798T + 0.08484DLI + 0.00802T^{2}$ - 0.000306T*DLI with R² = 0.46.



Figure 19. Response surface for *Tagetes* node number at finish as a function of average daily temperature (T) and average daily light integral (DLI). Each point may represent more than one observation. The equation for the response surface was y = 4.79135 - 0.16583T+ $0.00355T^2 + 0.01463DLI$ with $R^2 = 0.10$



Figure 20. The influence of temperature and daily light integral (DLI) on visible bud percentage at the finish plug stage in *Tagetes*.

SECTION III

Quantifying the Effects of Temperature and Daily Light Integral on Finish Bedding

Plant Growth and Development

Quantifying the Effects of Temperature and Daily Light Integral on Finish Bedding Plant Growth and Development

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Additional index words: Celosia, Impatiens, Salvia, Tagetes.

Received for publication ______. Accepted for publication ______. We gratefully acknowledge funding from growers providing support for Michigan State University floriculture research.

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Introduction

Production of garden plants is of major economic importance to the floriculture industry. In 2000, greenhouse growers in the United States produced garden plants with a wholesale value of \$2.12 billion, representing 50% of the wholesale value of all reported floricultural crops (USDA, 2001). The production of spring bedding plants in northern climates in the winter and early spring forces growers to rely on greenhouse heating. In recent years, fuel prices have fluctuated dramatically, and in response to energy expenses, growers may reduce their temperature settings to reduce their monthly fuel consumption. Although these methods may save in short-term fuel costs, crop timing and plant quality may be compromised in the process.

Daily light integral (DLI) varies by latitude and by time of year. In northern climates, DLIs can be quite low during winter and early spring. The amount of light plants receive in a greenhouse is not only affected by the amount of ambient solar radiation, but also by interference from greenhouse glazing and structures, which can reduce light by 40%. For example, outdoor light levels in midsummer in East Lansing, Michigan average about 45 mol·m⁻²·d⁻¹, and in midwinter average about 10 mol·m⁻²·d⁻¹ (Niu et al., 2001a). Thus, a typical greenhouse will transmit at most an average of 6 to 27 mol·m⁻²·d⁻¹ during the year. Under lower light levels, growers may consider the use of supplemental lighting to improve plant quality. However, whether the benefits of supplemental lighting outweigh the economic costs has not been determined for many bedding plants primarily because the effects of DLI on plant growth and development have not been determined.

Due to the value of bedding plants and the need for energy efficient production, the growth and development of bedding plants must be well understood and quantified. The effects of temperature and DLI have been studied on some economically important bedding plants, such as petunia (*Petunia ×hybrida* Hort.Vilm.-Andr.), pansy (*Viola ×wittrockiana* Gams.), vinca (*Catharanthus roseus* L.), and seed geranium (*Pelargonium ×hortorum* Bailey) (Adams et al., 1997; 1999; Armitage et al., 1981; Pietsch et al., 1995). Although these studies provide information on plant response to temperature and light intensity, more research in this area is warranted due to the variability of optimum temperatures and light requirements among species and between developmental processes. Additionally, to our knowledge, few recent scientific studies on temperature and DLI interaction have been published on other economically important floricultural crops, such as impatiens (*Impatiens wallerana* Hook.f.) and marigold (*Tagetes patula* L.).

The objectives of this research were to quantify the effects of temperature and DLI on progress to flowering and plant appearance at flowering (dry weight, height, node number, flower number, and flower size) of four popular bedding plants: *Celosia*, *Impatiens*, *Salvia*, and *Tagetes*.

Materials and Methods

Seedling plug culture. Seeds of Celosia argentea var. plumosa L. 'Gloria Mix', Impatiens wallerana Hook.f. 'Accent Red', Salvia splendens F. Sello ex Roem & Schult. 'Vista Red', and Tagetes patula L. 'Bonanza Yellow' were sown in 288-cell plug trays on 25 January 2002 and 2 April 2002 at a wholesale plug producer (Raker's

Acres, Litchfield, Mich.). The germinated seeds were received at Michigan State University on 29 January 2002 and on 8 April 2002. The 288-cell trays were placed in a growth chamber set at 23 °C under 150 μ mol·m⁻²·s⁻¹ provided by incandescent and fluorescent lamps with a 16-h photoperiod. Chambers were set at a vapor pressure deficit of 0.7 kPa. Plugs were top irrigated with well water (containing 95, 34, and 29 mg·L⁻¹ Ca, Mg, and S, respectively) supplemented with a water soluble fertilizer to provide the following (mg·L⁻¹): 40 N, 4 P, 40 K, 5 Ca, 0.3 Fe, 0.03 B and Mo, and 0.2 Mn, Zn, Cu (MSU Special; Greencare Fertilizers, Chicago, IL). Water was acidified with H₂SO₄ to a titratable alkalinity of ≈140 mg·L⁻¹ CaCO₃. Seedling were grown until deemed ready for transplant, which was 19, 23, 26, and 26 days from seed, for *Tagetes, Impatiens, Salvia*, and *Celosia*, respectively.

Greenhouse temperature and DLI treatments. For each species, 150 seedlings were removed from the growth chamber and transplanted into 10-cm pots containing 70% peat moss, 21% perlite, and 9% vermiculite (SUREMIX, Michigan Grower Products, Inc., Galesburg, Mich.). Plants were placed into 5 glass greenhouse compartments set at constant 14, 17, 20, 23, and 26 °C. Greenhouse air temperature was measured by a thermocouple placed in an aspirated box, and shoot tip temperature was measured by a thermocouple inserted \approx 2 mm below a plant shoot-tip under ambient light conditions. Within each compartment, ten pots were placed under each of three DLI treatments: ambient light with 50% shade cloth (OLS 50; Ludvig Svensson, Charlotte, NC), ambient light, and ambient plus supplemental lighting from high pressure sodium lamps (\approx 170 µmol·m⁻²·s⁻¹). Plants in all treatments were exposed to a 16-h photoperiod, from 0600 HR to 2200 HR, using HPS lamps which delivered \approx 34, \approx 75, \approx 170 µmol·m⁻²·s under the ambient light plus 50% shade cloth, ambient light, and ambient plus supplemental high-pressure sodium, respectively. Line quantum sensors (Apogee Instruments, Inc. Logan, Utah) were placed under the three lighting treatments in three of the five greenhouse compartments to measure photosynthetic photon flux (PPF). Instantaneous values were converted to daily light integrals (DLI), which were used for analysis. Vapor pressure deficit was maintained at \approx 0.7 kPa by steam injection. A CR10 data logger (Campbell Scientific, Logan, Utah) recorded the environmental data every 10 seconds and hourly averages were reported (Table 1 and 2).

Plants were top irrigated as necessary with well water (containing 95, 34, and 29 mg·L⁻¹ Ca, Mg, and S, respectively) supplemented with a water soluble fertilizer to provide the following (mg·L⁻¹): 125 N, 13 P, 125 K, 15 Ca, 1 Fe, 0.1 B and Mo, and 0.5 Mn, Zn, Cu (MSU Special; Greencare Fertilizers, Chicago, IL) acidified with H_2SO_4 to a titratable alkalinity of 140 mg·L⁻¹ CaCO₃. Date of flower, plant height from soil level, node number on the primary shoot, total shoot dry weight, flower number, and flower size were recorded at open flower. *Tagetes* and *Impatiens* were considered open when all petals were fully reflexed. *Celosia* was considered in flower when the inflorescence reached 4 cm long, and *Salvia* when the bottom floret was open.

Data were analyzed using average air temperature and DLI for each individual plant from transplant to flowering. Flowering data were converted to rates by taking the reciprocal of number of days to flowering. Multiple regression analysis was performed

using SAS (SAS Institute Inc., Cary, NC) response surface regression (RSREG procedure) to determine the effect of DLI in combination with air temperature. Similar studies with temperature and DLI have used similar forms of analysis (Adams et al. 1997; Carew et al., 2003). If P > 0.05 for the contribution of individual terms to the model, the terms were removed, and regression (REG procedure) was used to determine the model coefficients. Equations were then used to generate predicted models. Approximately 300 observations were used to generate each model. Base temperatures, under 5 and 15 mol·m⁻²·d⁻¹, were calculated by inserting the appropriate DLI into the rate of progress to flower equation and setting the equation equal to zero. **Results**

Celosia. Rate of progress to flowering was related quadratically with temperature and DLI (Table 3). Within the range of observed DLI, rate of progress to flowering increased up to ≈ 25 °C (Fig. 1). Increasing the DLI from 5 to 15 mol·m⁻²·d⁻¹, accelerated flowering rate, but further increases in DLI had a negligible effect on rate of progress to flower. The model predicted days to flower within ± 5 days for 68% of the actual data (Fig. 6). Calculated base temperatures under 5 and 15 mol·m⁻²·d⁻¹ were 11.7 and 10.2 °C, respectively.

Plant height was primarily affected by temperature, increasing with increasing temperature and the largest differences in height due to DLI were observed at 28 °C (Fig. 2). Dry weight increased as temperature and especially DLI increased (Fig. 3). For example, at 14 °C, plants under 5 mol·m⁻²·d⁻¹ averaged 1.6 g while those under 25 mol·m⁻²·d⁻¹ averaged 5.8 g. Node number at flowering was greatest in plants that

received 25 mol·m⁻²·d⁻¹, but differences in node number in plants receiving < 20 mol·m⁻²·d⁻¹ were small (Fig. 4). However, node number had a low coefficient of determination ($R^2 = 0.23$) (Table 3). Under 25 mol·m⁻²·d⁻¹, flower number was greatest at ≈ 22 °C, and began to decrease as temperature increased or decreased (Fig.5). Under 5 mol·m⁻²·d⁻¹, flower number was maximal at ≈ 16 °C, and decreased as temperature increased to 28 °C. Flower size was not recorded for *Celosia*, as the length of the inflorescence was used to determine when plants were in flower.

Impatiens. Rate of progress to flowering increased quadratically as temperature increased from 14 to 28 °C (Fig. 7). The model predicted days to flower within \pm 5 days for 70% of the actual data (Fig. 6). Base temperatures calculated under 5 and 15 mol·m⁻²·d⁻¹ were 7.5 and 4.3, respectively.

Plant height at flowering increased under all DLIs as temperatures increased from 14 to 21°C and decreased thereafter (Fig. 8). Additionally, plant height increased as DLI increased at all temperatures studied. However, the coefficient of determination for the model was relatively low ($R^2=0.21$). Dry weight increased as DLI increased at all temperatures studied; at 20 °C, dry weight was \approx 72% less under 5 than 25 mol·m⁻²·d⁻¹ (Fig. 9). Node number was not recorded for *Impatiens*. Flower size decreased as temperature increased from \approx 15 °C to 28 °C, and the effects of DLI were relatively small (Fig. 10). Flower number decreased with increasing temperature and increased with increasing DLI. For example, at 14 °C, flower number increased by \approx 88% as DLI increased from 5 to 25 mol·m⁻²·d⁻¹, and at 26 °C, flower number increased by \approx 330% (Fig. 11). Salvia. Rate of progress to flower increased quadratically as temperature and DLI increased, and an optimum temperature was not observed in the temperatures tested (Fig. 12). The model predicted days to flower within \pm 5 days for 90% of the actual data (Fig. 16). Base temperatures calculated under 5 and 15 mol·m⁻²·d⁻¹ were 7.3 and 6.8 °C, respectively.

Plant height increased with temperature under all DLIs until a maximum at ≈ 20 °C under 5 mol·m⁻²·d⁻¹ and at ≈ 24 °C under 25 mol·m⁻²·d⁻¹; beyond that maximum, plant height decreased (Fig. 13). However, the R² value was low (0.21). Plant height decreased with increasing DLI at temperatures ranging from 14 through 26 °C. Dry weight increased as temperature decreased regardless of DLI (Fig. 14). Node number at flowering and flower size were not significantly affected by temperature or DLI (data not presented). Flower number generally decreased with increasing temperature, but was between 9 and 11 when temperature was ≤ 20 °C (Fig. 15).

Tagetes. Rate of progress to flowering increased as DLI and temperature increased (Fig. 17), and an optimum was not reached in the observed temperature range. The model predicted days to flower within ± 5 days for 91% of the actual data (Fig. 16). Base temperatures calculated under 5 and 15 mol·m⁻²·d⁻¹ were both -3.9 °C. Plant height increased linearly with increasing temperature and DLI, although the r² value was low (0.23) (Fig. 18). Dry weight was greatest at the coolest temperatures and highest DLI, and decreased with increasing temperature (Fig. 19). At 14 °C, dry weight increased by 100% as DLI increased from 5 to 25 mol·m⁻²·d⁻¹. Flower number and flower size both decreased linearly as temperatures increased from 14 to 28 °C and DLI decreased from 25 to 5 mol·m⁻²·d⁻¹ (Fig. 20 and 21). Under 25 mol·m⁻²·d⁻¹, flowers were 84% smaller and 42% fewer when they flowered at 28°C compared with plants grown at 14 °C.

Discussion

Days to flowering was significantly affected by both temperature and DLI in all species. In the observed temperature and DLI ranges, T_{opt} were observed in *Celosia* ($\approx 25 \text{ °C}$) and *Impatiens* ($\approx 26 \text{ °C}$), but not in *Salvia* and *Tagetes*. Increasing the DLI increased progress to flowering in *Salvia* and *Tagetes*, but above 15 mol·m⁻²·d⁻¹, there was little increase in rate progress to flower in *Celosia*. The effect of DLI on *Impatiens* varied with temperature, and at >20 °C, the model predicts a delay in flowering at > 15 mol·m⁻²·d⁻¹. This may indicate a maximum in photosynthetic capacity for these plants, which is not surprising since *Impatiens* can be considered a shade-tolerant plant.

The increase in rate of progress to flower attributed to DLI for these species may be at least partially due to increased plant temperature under the higher DLI treatments. Studies on vinca (*Catharanthus roseus* L.) showed that shoot tip temperature can be greater than air temperature when under higher light intensities (Faust and Heins, 1997). Shoots receiving supplemental HPS lighting of 50, 75, and 100 μ mol·m⁻²·s⁻¹ were 1.2, 1.5, and 1.7 °C higher, respectively, than that of plants in the dark (Faust and Heins, 1997). Because node number was not significantly influenced by temperature or DLI in *Salvia* or *Tagetes* (data not shown), the differences in time to flower could primarily be a function of plant temperature. In contrast, temperature and DLI influenced node number at flowering in *Celosia*. Node number

below the inflorescence of *Celosia* increased as temperature increased from 20 to 28 °C, and was also greater under the highest DLIs, although the coefficient of determination was quite low ($r^2 = 0.20$). Additionally, low light can affect plant development by limiting the supply of photosynthate. This could also be a contributing factor to decreases in rate of flowering under the lower light levels.

The models developed varied in accuracy, with *Salvia* and *Tagetes* generally being the most accurate (> 90% of the actual data was within \pm 5 days of the predicted), and *Celosia* and *Impatiens* containing more variability. Actual days to flower was greater than predicted in the models for *Celosia* and *Impatiens* as evidenced by the skewed frequency diagrams. Some of the variability may be explained by genetic variability within the seed populations. Additionally, the selected cultivar for *Celosia* was 'Gloria Mix', which may have had more variability than if a single color cultivar had been studied. Further independent experimentation could be performed to strengthen the validity of each model.

Dry weight at flower increased as DLI increased from 5 to 25 mol·m⁻²·d⁻¹ in all species, except for *Salvia*, which reached an optimum dry weight under $\approx 15 \text{ mol·m}^{-2}$ ·d⁻¹. Dry weight also decreased with increasing temperature in all species except for *Celosia*. A previous study on campanula showed similar results; as average daily plant temperature decreased from 25 to 15 °C, dry weight decreased linearly under a DLI of 10.8 and 15.8 mol·m⁻²·d⁻¹ (Niu et al., 2001b). Dry weight increased by $\approx 155\%$ when DLI increased from 4.2 to 10.8 mol·m⁻²·d⁻¹ and by 25% when DLI increased from 10.8 to 15.8 mol·m⁻²·d⁻¹ (Niu et al., 2001b). In contrast, in our study with *Celosia*, dry

weight increased with increasing temperature. This may be explained by the chlorotic growth that was observed at cooler temperature treatments, indicating a decreased ability to harvest light. This is likely why dry weight increased with temperature, especially at the higher DLIs, even though plants grew for a longer period of time before flowering at the cooler temperatures.

Flower number at first open flower generally decreased as temperature increased because time to flowering was reduced as temperature increased. Thus, plants had a longer duration to produce photosynthates when grown at the cooler temperatures which could be used for flower production. In previous studies with coreopsis (Coreopsis grandiflora Hogg ex Sweet. 'Sunray'), rudbeckia (Rudbeckia fulgida Ait. 'Goldsturm'), and Shasta daisy (Leucanthemum × superbum Bergman ex. J. Ingram 'Snowcap'), flower bud number at time of flowering decreased 80%, 75%, and 55%, respectively, as temperature increased from 16 °C to 26 °C (Yuan et al., 1998). In campanula (*Campanula carpatica* Jacq. 'Blue Clips'), the number of flower buds decreased linearly, at 10 flowers per °C, as plant temperature increased from 16 to 24 $^{\circ}$ C (under ambient CO₂ concentration) (Niu et al., 2001). Our data suggest a similar response, with flower number decreasing as temperature increased in all four bedding plant species. Additionally, in Celosia, Impatiens, and Tagetes, flower number increased as DLI increased at all temperatures studied. However, flower number of Salvia began to decrease when temperature was below ≈ 20 °C and DLI was >15 mol·m⁻ $^{2} \cdot d^{-1}$.

Flower size was not significantly influenced by temperature or DLI in Salvia and was not measured in *Celosia* as length of the flower was used to determine time of flower. Flower size of Impatiens and Tagetes increased as temperature decreased. This can also be explained by the ability of plants to harvest increasingly more light at the lower temperatures, since the rate of progress to flower was slower at the lower temperatures. Increasing the DLI also increased flower size of Impatiens and Tagetes, but in *Impatiens*, it reached a maximum between 10 and 15 mol·m⁻²·d⁻¹. Other studies indicate similar relationships. In campanula, at temperatures ranging from 14 to 26 °C, flowers were $\approx 10-15\%$ larger under 17 than under 5 mol·m⁻²·d⁻¹ (Niu et al., 2001). Similarly, flower size in vinca was 15-20% greater when plants were grown under a DLI of $\approx 29 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ at temperatures ranging from 15 to 35 °C, compared with plants under ≈ 18 and $\approx 9 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ (Pietsch et al., 1995). In geranium 'Sooner Red', flowers were smaller under shade than under ambient conditions (Armitage and Wetzstein, 1984).

Except for *Tagetes*, the estimated base temperature for rate of progress to flowering for these species differed under different DLIs, with the largest difference occurring in *Impatiens* (3.2 °C) as DLI increased from 5 to 15 mol·m⁻²·d⁻¹. *Tagetes* had the lowest base temperature of the species studied at -3.9 °C. *Salvia* (7.3 and 6.8 °C) and *Impatiens* (7.5 and 4.3 °C) had similar base temperatures and *Celosia* had the highest base temperatures (11.7 and 10.2 °C). If short-term heating costs were of concern, *Tagetes*, *Impatiens*, and *Salvia* could be grown cooler, and higher quality could be obtained, although time to flower would be increased. However, *Celosia*, having a much higher base temperature, could not be successfully produced under cooler temperatures, so warmer temperatures >20 °C would be recommended.

Supplemental lighting could be beneficial for all species under naturally low light levels to reduce days to flower and in most cases, increase quality. For *Celosia*, hastening of flowering only occurred with DLIs up to 15 mol·m⁻²·d⁻¹. So, if natural light levels are already moderately high, supplemental lighting would have little or no effect on time to flower. Similarly, in *Impatiens*, at temperatures >20 °C, the model predicted that a DLI >15 mol·m⁻²·d⁻¹ delayed time to flower, so supplemental lighting would not be beneficial. For *Salvia* and *Tagetes*, time to flower continued to decrease with increasing DLI to 25 mol·m⁻²·d⁻¹, which was the greatest DLI recorded in these experiments.

Increasing daily light integral may be beneficial for decreasing time to flower and improving plant quality, but the economic costs to install and maintain supplemental lighting should be considered. Using a financial lighting model presented by Fisher and Donnelly (2002), we developed an economic scenario to demonstrate how timing information can be utilized. If a crop of *Celosia* were grown at 20 °C and the DLI was $\approx 5 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, it would take 43 days to flower. With an additional 5 mol $\cdot \text{m}^{-2} \cdot \text{d}^{-1}$, it would take 37 days to flower. Assuming the use of 400W HPS lamps, lighting for 16 weeks per year, the lamps lasting 15 years, and the bulbs lasting 12,000 hours, the cost without lighting amounts to $0.92/\text{ft}^2/\text{crop}$ and with lighting, \$1.58/ft²/crop (Table 4). The cost to install lamps and provide electricity would exceed

the amount of overhead one would save by increasing the crop time, so lighting would not be beneficial in this scenario.

The information presented here can allow growers to predict crop timing and plant quality under a wide range of temperatures and DLIs in 4 bedding plant cultivars. This information can then be used to weigh the costs and benefits of timing and quality with economic costs.

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Replication	Shoot-tip temperatures °C					Air temperatures °C				
	14	17	20	23	26	14	17	20	23	26
1	16.1	17.4	20.5	23.3	26.4	15.1	17.4	20.3	24.2	26.7
2	17.7	18.9	20.5	25.7	26.9	16.8	17.6	20.7	25.5	27.1

Table 1. Air temperature and average shoot-tip temperature of plants (*Tagetes*) under ambient light treatments grown in glass greenhouses at the indicated setpoints.

 Table 2.
 Daily light integral (DLI) under treatments.

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Replication	Treatment	Average DLI $(mol \cdot m^{-2} \cdot d^{-1})$
1	Ambient light plus 50% shade cloth	7.6
	Ambient	15.8
	Ambient plus HPS	21.6
2	Ambient light plus 50% shade cloth	11.4
	Ambient	21.2
	Ambient plus HPS	25.6

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Table 3. Parameters of regression analysis relating rate of progress to flower, height, dry weight, node number, flower number,

and flow Coeffici	ver size for (ents for mod	<i>Celosia, Impatiens,</i> lel equations were	Salvia, and Tage used to generate I	ttes to temperatur Figures 1-19.	e (T) in °C and da	aily light integral ((DLI) in mol·m ⁻² ·d	<u>.</u> .
Species	Parameter	Intercept	T	T ²	DLI	DL1 ²	T*DLI	r ²
Celosia	1/Days to flower	-7.229E-2 ± 8.370E-3 ^Z	7.400E-3 ± 7.920E-4	-1.447E-4 ± 1.862E-5	1.260E-3 ± 2.180E-4	-3.119E-5 ± 6.630E-6	۲.	0.67
	Height	4.589 ± 1.434	0.9687 ± 0.0953	:	ł	0.0103 ± 3.490E-3	-0.0229 ± 5.190E-3	0.43
	Dry weight	1.004 ± 0.239	ł	$3.940E-3 \pm 4.330E-4$	1	5.900E-3 ± 3.766E-4	:	0.53
	Node number	31.01 ± 6.667	-1.283 ± 0.6295	0.0368 ± 0.0148	-0.3290 ± 0.1674	0.0153 ± 5.280E-3	1	0.20
	Flower	3.011 ± 7.0142	1.660± 0.6502	-0.0592 ± 0.0152	-0.4488 ± 0.1609	ł	0.0408 ± 7.580E-3	0.46
Impatiens	1/Days to							
-	flower	-0.0480 ± 0.0148	5.702E-3 ± 1.397E-3	-7.980E-5 ± 3.352E-5	2.142E-3 ± 4.890E-4	-3.291E-5 ± 1.107E-5	-6.484E-5 ± 1.621E-5	0.41
	Height	-4.259 ± 3.581	1.209 ± 0.3522	-0.0270 ± 8.370E-3	:	4.180E-3 ± 5.452E-4	:	0.21
	Dry weight	1.465 ± 0.2045	ł	-1.490E-3 ± 3.729E-4	:	4.120E-3 ± 3.187E-4	1	0.38
	Flower size	3.880 ± 0.6533	0.1627 ± 0.0632	-6.270E-3 ± 1.500E-3	0.0648 ± 0.0157	-0.0019 ± 4.980E-4	1	0.62
	Flower	92.904 ± 4.899	;	-0.1130 ± 8.920E-3	:	0.0981± 7.780E-3	:	0.53
	number							
Salvia	1/Days to							
	flower	-0.0241 ± 7.430E-3	3.790E-3 ± 7.345E-4	-5.585E-5 ± 1.756E-5	:	1	2.396E-5 ± 1.870E-6	0.80
	Height	4.4506 ± 2.835	1.248 ± 0.2674	-0.0323 ± 6.340E-3	-0.3005 ± 0.0688	:	0.0114 ± 3.280E-3	0.21
	Dry weight	4.8305± 0.2555	-0.1547± .0168	:	1	-2.020E-3 ± 6.617E-4	3.230E-3 ± 9.468E-4	0.37
	Flower	14.024 ± 0.6894	ł	-0.0131 ± 1.430E-3	-0.3821 ± 0.0763	;	0.0212 ± 3.650E-3	0.34
	number							
Tagetes	1/Days to							
	flower	$4.470E-3 \pm 1.400E-3$	$1.150E-3 \pm 7.512E-3$	ł	:	1	4.197E-5 ± 2.210E-6	0.79
	Height	8.180 ± 0.4889	0.1651 ± 0.0208	ł	0.0725 ± 0.0148	ł	:	0.23
	Dry weight	1.608 ± 0.1219	1	-1.320E-3 ± 1.861E-4	0.0473± 5.51E-3	ł	ł	0.30
	Flower size	7.002 ± 0.1275	-0.1254 ± 5.420E-3	ł	0.0317 ± 3.840E-3		:	0.67
	Flower	28.11 ± 1.565	-0.7310 ± 0.0668	ł	0.2567 ± 0.0472	1	:	0.34
	number							

Table 3. Parameters of regression analysis relating rate of progress to flower, height, dry weight, node number, flower number,

^z Standard error.

^Y Parameter is not significant.

Table 4. Theoretical example of the cost of supplying an additional 5 mol·m⁻²·d⁻¹ of HPS lighting to *Celosia* grown at 20 °C. Assuming 4" plant spacing, electricity costs = $0.099/ft^2/wk$ and overhead from lamp installation and maintenance = $0.051/ft^2/wk$. Financial information and assumptions taken from Fisher and Donnelly, 2002.

			Lighting	Overhead	Total cost
	DLI	Days to	cost per ft ² /	cost per ft ² /	per ft ² /
Scenario	$(\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1})$	flower	week	week	crop
Natural light	5	43	0	\$0.15	\$0.92
Supplemental	10	37	\$0.149	\$0.15	\$1.58
light					

> Fig of in



Figure 1. Temperature and daily light integral effects on *Celosia* rate of progress toward flowering. The model was generated using the coefficients in Table 3.



Figure 2. Temperature and daily light integral (DLI) effects on *Celosia* height at flowering. The model was generated using the coefficients in Table 3.



Figure 3. Temperature and daily light integral (DLI) effects on *Celosia* dry weight at flowering. The model was generated using the coefficients in Table 3.



Figure 4. Temperature and daily light integral (DLI) effects on *Celosia* node number at flowering. The model was generated using the coefficients in Table 3.


Figure 5. Temperature and daily light integral (DLI) effects on *Celosia* flower number. The model was generated using the coefficients in Table 3.



Figure 6. Frequency of predicted minus actual days to flower in *Celosia* and *Impatiens*. The total number of plants observed under temperatures ranging from 14 to 26 °C and daily light integrals from 4 to 26 mol·m⁻²·d⁻¹ was 296 and 298, respectively.



Figure 7. Temperature and daily light integral (DLI) effects on *Impatiens* rate of progress toward flowering. The model was generated using the coefficients in Table 3.



Figure 8. Temperature and daily light integral (DLI) effects on *Impatiens* height at flowering. The model was generated using the coefficients in Table 3.



Figure 9. Temperature and daily light integral (DLI) effects on *Impatiens* dry weight at flowering. The model was generated using the coefficients in Table 3.



Figure 10. Temperature and daily light integral (DLI) effects on *Impatiens* flower size. The model was generated using the coefficients in Table 3.



Figure 11. Temperature and daily light integral (DLI) effects on *Impatiens* flower number. The model was generated using the coefficients in Table 3.



Figure 12. Temperature and daily light integral (DLI) effects on *Salvia* rate of progress toward flowering. The model was generated using the coefficients in Table 3.



Figure 13. Temperature and daily light integral (DLI) effects on *Salvia* height at flowering. The model was generated using the coefficients in Table 3.



Figure 14. Temperature and daily light integral (DLI) effects on *Salvia* dry weight at flowering. The model was generated using the coefficients in Table 3.



Figure 15. Temperature and daily light integral (DLI) effects on *Salvia* flower number. The model was generated using the coefficients in Table 3.



Figure 16. Frequency of predicted minus actual days to flower in Salvia and Tagetes. The total number of plants observed under temperatures ranging from 14 to 26 °C and daily light integrals from 4 to 26 mol·m⁻²·d⁻¹ was 300 and 292, respectively.



Figure 17. Temperature and daily light integral (DLI) effects on *Tagetes* rate of progress toward flowering. The model was generated using the coefficients in Table 3.



Figure 18. Temperature and daily light integral (DLI) effects on *Tagetes* height. The model was generated using the coefficients in Table 3.



Figure 19. Temperature and daily light integral (DLI) effects on *Tagetes* dry weight. The model was generated using the coefficients in Table 3.



Figure 20. Temperature and daily light integral (DLI) effects on *Tagetes* flower size. The model was generated using the coefficients in Table 3.



Figure 21. Temperature and daily light integral (DLI) effects on *Tagetes* flower number. The model was generated using the coefficients in Table 3.

SECTION IV

Effects of Daily Light Integral on Bedding Plant Plugs and Subsequent Growth and

Development

Effects of Daily Light Integral on Bedding Plant Plugs and Subsequent Growth and Development

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Additional index words: Celosia, Impatiens, Salvia, Tagetes, Viola.

Received for publication ______. We gratefully acknowledge funding from greenhouse growers providing support for Michigan State University floriculture research. Additional thanks to David Joeright for assistance in experimental setup.

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Introduction

Daily light integral (DLI) is the cumulative amount of photosynthetic light received and it is expressed in mol·m⁻²·d⁻¹. DLI varies by latitude and by time of year. Mean DLI ranges from 5 to 10 mol·m⁻²·d⁻¹ across the Northern U.S. in December to 55 to 60 mol·m⁻²·d⁻¹ in the Southwestern U.S. in May through July (Korczynski et al., 2002). The primary differences in DLI from May through August occur between the eastern and western U.S. due to regional weather patterns and elevation. From October through February, differences occur between the northern and southern U.S. due to differences in solar duration and quantum fluxes (Korczynski et al., 2002).

The amount of light plants receive in a greenhouse is reduced by the interference from greenhouse glazing and structures. For example, the DLI outdoors in midsummer in East Lansing, Michigan average $\approx 45 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, and in midwinter average $\approx 10 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ (Niu et al., 2001). Due to glazing and structures, light transmission is often reduced by about 40%. Thus, a typical greenhouse in Michigan will transmit an average of ≈ 6 to 27 mol $\cdot \text{m}^{-2} \cdot \text{d}^{-1}$ during the year.

During the winter months in northern climates, low DLIs may lead to poor plant quality and slower plant development. For example, in petunia, a DLI of 6.6 rather than 13 mol \cdot m⁻²·d⁻¹ increased time to flower by up to 3 weeks (Kaczperski et al., 1991). Since the advent of plug technology, few scientific studies have been published on the effects of daily light integral (DLI) on bedding plant plug growth and development. In addition, the effects of DLI during the plug stage on subsequent bedding plant growth and development have not been investigated to our knowledge.

DLI is known to affect dry weight and height. For example, the dry weight of *Petunia* ×*hybrida* (Graper et al., 1990;Graper and Healy, 1992; Lieth et al, 1991), *Begonia semperflorens* (Graper and Healy, 1990), *Viola* ×*wittrockiana* (Adams et al, 1997), and *Pelargonium* ×*hortorum* (White and Warrington, 1988) increased as DLI increased, although the dry weight generally increases at a decreasing rate as DLI increases. An increase in DLI decreased height in *Pelargonium* ×*hortorum* (Erickson et al., 1980) and *Impatiens wallerana* (Dressen and Langhans, 1992).

Increasing DLI hastened time to flowering in *Pelargonium* ×hortorum (Carpenter and Rodriquiz, 1971; Erickson et al., 1981; Armitage and Wetzstein, 1984), *Matthiola incana* (Dansereau et al., 1998), and *Petunia* ×hybrida (Kacsperski et al., 1991). However, increasing DLI from 4 to 16 mol·m⁻²·d⁻¹, did not have an effect on time to flower in *Campanula carpatica* (Niu et al., 2001b).

Quality characteristics such as flower size and flower number can be affected by DLI. Generally, the number and size of flowers increases as DLI increases. This trend has been observed in species such as *Pelargonium* ×*hortorum* (Armitage and Wetzstein, 1984) and *Catharanthus roseus* (Pietsch et al., 1995). In *Campanula* 'Deep Blue Clips', flower size and number were similar when grown under DLIs ranging from 5 to 17 mol·m⁻²·d⁻¹ before visible bud (Niu et al., 2001). Supplemental lighting after visible bud partially compensated for smaller flower number under higher temperatures; the number of flower buds was \approx 40% higher under 17 mol·m⁻²·d⁻¹ after

visible bud at 22 to 24 °C than under 5.7 mol·m⁻²·d⁻¹ at 14 to 16 °C (Niu et al., 2001). Flower size also increased as DLI increased after visible bud; at temperatures ranging from 14 to 26 °C, flowers were \approx 10-15% larger under 17 mol·m⁻²·d⁻¹ than under 5 mol·m⁻²·d⁻¹ (Niu et al., 2001).

Several studies have been published on the effects of DLI from seedling stage until flowering, but little information is available on the effects of DLI specifically during the seedling stage. Goals of this research were to investigate the effects of DLI on growth, development, and quality of five popular bedding plant species as young plants and to determine if there were any residual effects of DLI on subsequent growth and development after transplant.

Materials and Methods

Initial DLI treatments. Seeds of Celosia argentea var. plumosa 'Gloria Mix', Impatiens wallerana 'Accent Red', Salvia splendens 'Vista Red', Tagetes patula 'Bonanza Yellow', and Viola ×wittrockiana 'Crystal Bowl Yellow' were sown into 288cell trays at a wholesale plug producer (Raker's Acres, Inc. Litchfield, Mich). Five days after sowing, trays were delivered and randomly placed in three Conviron E15 growth chambers (Winnipeg, Canada). A high light (HL) chamber was fitted with six 160W fluorescent tubes and ten 25W incandescent bulbs; the medium light (ML) chamber was fitted with eight fluorescent tubes (four painted black) and ten incandescent bulbs (four painted black); and the low light chamber was fitted with ten fluorescent tubes (eight painted black), and six incandescent bulbs (three painted black). Bulbs were painted black to provide differing light intensities while producing a similar

thermal load in each chamber. Each chamber was set at ≈ 21 °C with minor adjustments made so that plant temperature was 21°C. A vapor pressure deficit (VPD) of 0.6 kPa was maintained. In each chamber, air temperature was monitored by an aspirated thermocouple, plant temperatures were monitored by a thermocouple placed in the shoot tip, and canopy temperature was monitored by an infrared sensor (IRt/c.01, Exergen Corp., Watertown, MA) placed at a 45^c angle above the canopy. Light intensity was monitored with a line quantum sensor (Apogee Instruments, Inc., Logan, Utah) and a quantum sensor (LI-COR, Lincoln Nebr.). A CR10 data logger (Campbell Scientific, Logan, Utah) recorded the environmental data every 10 seconds and hourly averages were recorded. Actual average temperature, shoot-tip temperature, VPD, and DLI from the start of treatments to the end of the plug stage were calculated (Tables 1 and 2). The red (600 to 700 nm) to far-red (700-800 nm) ratio (photons) was determined each chamber with a spectroradiometer (LI-COR, LI-1800, Lincoln, Nebr.) and was 3.56, 3.56, and 3.58 for the HL, ML, and LL chambers, respectively. Plugs were subirrigated with well water (containing 95, 34, and 29 mg L^{-1} Ca, Mg, and S, respectively) supplemented with a water soluble fertilizer to provide the following (mg·L⁻¹): 40 N, 4 P, 40 K, 5 Ca, 0.3 Fe, 0.03 B and Mo, and 0.2 Mn, Zn, Cu acidified with H₂SO₄ to a titratable alkalinity of \approx 140 mg·L⁻¹ CaCO₃ (MSU Special; Greencare Fertilizers, Chicago, IL).

Common Environment. Sixteen plugs (8 from each block) of Tagetes, Celosia, Impatiens, Salvia, and Viola were transplanted after 18, 19, 22, 22, and 26 days under the initial DLI treatments, respectively. Plant height from soil level to shoot apex, node number, shoot dry weight, and visible flower bud (if present) were recorded at transplant. Plugs were potted into 10-cm pots with a 70% peat moss, 21% perlite, and 9% vermiculite potting media (SUREMIX, Michigan Grower Products, Inc., Galesburg, Mich.) and randomly placed in a common growth chamber (TC-2 Environmental Growth Chambers, Chagrin Fall, Ohio). Plants were top irrigated as necessary with well water supplemented with a water soluble fertilizer to provide the following (mg·L⁻¹): 125 N, 13 P, 125 K, 15 Ca, 1 Fe, 0.1 B and Mo, and 0.5 Mn, Zn, Cu (MSU Special; Greencare Fertilizers, Chicago, IL). Water was acidified with H₂SO₄ to a titratable alkalinity of \approx 140 mg·L⁻¹ CaCO₃.

The growth chamber was set at 21 °C, and a DLI of 8.5 mol·m⁻²·d⁻¹ was provided by fluorescent and incandescent lamps (16-h photoperiod). The vapor pressure deficit was set at 0.7kPa. DLI was monitored with a quantum sensor (LI-COR, Lincoln, Nebr.), plant temperature was monitored with thermocouples placed in the shoot tips, and air temperature was monitored by an aspirated thermocouple. Temperature and light values were recorded by a CR10 data logger (Campbell Scientific, Logan, Utah) every 10 seconds and hourly averages were recorded. The actual air temperature averaged 21.9 °C. When plants reached flowering, date of first open flower, plant height, node number below the first flower, flower number, flower size, and dry weight were recorded. *Salvia* was considered in flower when the bottom flower on the spike opened and *Celosia* was considered in flower when the inflorescence reached 4 cm in length. The experiment was performed twice, and data were analyzed using SAS (SAS Institute Inc., Cary, NC) general linear model (GLM

procedure). Regression procedures were performed in Sigma Plot (SPSS, Chicago, Illinois). Average shoot dry weight per average node number was calculated for each species and used as an indication of plug quality.

Results

Seedling stage. Node number increased as DLI increased from 4.1 to 14.2 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in all species except for Salvia (Table 3). In Celosia, Impatiens, Tagetes, and Viola, average dry weight per node increased linearly with DLI and by 64%, 47%, 64%, and 68% respectively, as DLI increased from 4.1 to 14.2 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (Fig.1). Salvia dry weight per node increased from 0.006 to 0.014 g·node⁻¹ as DLI increased until a maximum at $\approx 12 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$.

Quadratic relationships relating DLI to height were observed in all species measured (Fig. 2). As DLI increased from 4.1 to 14.2 mol·m⁻²·d⁻¹, height of *Impatiens* and *Salvia* decreased by 27% and 37%. As DLI increased from 4.1 to 14.2 mol·m⁻²·d⁻¹, height of *Tagetes* increased from 3.1 to 3.4 cm and height of *Celosia* increased from 2.5 to 2.8 cm. *Viola* height was not recorded.

Impatiens and Tagetes were the only genera to have visible flower buds at the time of transplant, and as DLI increased, the percentage of plugs at visible bud generally increased (Fig. 3). Thirty-eight percent of Impatiens plugs under 14.1 mol·m⁻²·d⁻¹ were in bud, while plugs grown under 4.1 or 4.5 mol·m⁻²·d⁻¹ had no flower buds. All Tagetes plugs were in bud at time of transplant under \geq 7.2 mol·m⁻²·d⁻¹, and only 56% of plants were in bud when grown under 4.1 mol·m⁻²·d⁻¹. Subsequent growth and development. Celosia. Time to flower decreased (by 10 days) as DLI during the plug stage increased from 4.1 to 14.2 mol·m⁻²·d⁻¹ (Fig. 4A). Correspondingly, node number below the first inflorescence decreased by 7 nodes as initial DLI increased from 4.1 to 14.2 mol·m⁻²·d⁻¹ (Fig. 4B). Flower number at first flower and dry weight decreased linearly (by $\approx 61\%$ and $\approx 31\%$, respectively) as the initial DLI increased within the range studied (Fig. 4C-D). Plant height at flowering also decreased linearly (from 22.2 to 18.7 cm) as initial DLI increased from 4.1 to 14.2 mol·m⁻²·d⁻¹ (Fig. 4E).

Impatiens. The relationship between days to flower after transplant and DLI was quadratic; days to flower decreased from 36 to a minimum of \approx 24 days as the initial DLI increased from 4.1 to \approx 12 mol·m⁻²·d⁻¹ (Fig. 5A). Additionally, node number below the first open flower decreased linearly, from 7 to 4 (Fig. 5B). Flower number and flower size decreased linearly from 49 to 20 (Fig. 5C) and from 5 to 4.5 cm, respectively (Table 3). As the initial DLI increased from 4.1 to 14.2 mol·m⁻²·d⁻¹, dry weight and height at first flower decreased linearly by 59% and 24%, respectively (Fig. 5D and E).

Salvia. Time to flower decreased by 11 days as initial DLI increased from 4.1 to 14.2 mol·m⁻²·d⁻¹ (Fig. 6A). Plants developed fewer nodes below the inflorescence when plugs were grown under higher DLIs, decreasing from 6 to 4 (Fig. 6B). Significant linear relationships were also observed between initial DLI and flower number, flower size, dry weight and height (Figure 6C to E, Table 3). As initial DLI increased from 4.1 to 14.2 mol·m⁻²·d⁻¹, flower number decreased from 2 to 1 and flower

size decreased from 4.1 to 3.1 cm. Dry weight and height at flowering decreased with increasing DLI by 62% and 25%, respectively.

Tagetes. Time to flower decreased by only 4 days as initial DLI increased from 4.1 to $\approx 11 \text{mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ (Fig. 7A). Node number decreased very slightly (from 4.3 to 3.5) as initial DLI increased from 4.1 to 14.2 mol·m⁻²·d⁻¹ (Fig. 7B). Flower number was not affected by the initial DLI treatments (Fig. 7C). Flower size decreased slightly (from 4.3 to 4.0 cm) as DLI decreased from 14.3 to 4.1 mol·m⁻²·d⁻¹ (Table 3). Dry weight decreased linearly as DLI increased (Fig. 7D). Height was quadratically related to the initial DLI (Fig. 7E).

Viola. Time to flower was hastened by 12 days as initial DLI increased from 4.1 to $\approx 11 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ (Fig. 8A). Flower number and dry weight decreased linearly from 11 to 7 and by 26%, respectively, as initial DLI increased from 4.1 to 14.2 mol $\cdot \text{m}^{-2} \cdot \text{d}^{-1}$ (Fig. 8C and 8D). Node number, flower size, and height at flowering were not significantly affected by the initial DLI treatments (Fig. 8B, 8E, Table 4).

Discussion

Although temperature is often considered to be the main environmental factor influencing plant rate of development, our study shows some influence of DLI. Average node number at transplant increased with increasing DLI, indicating increased developmental rates during the plug stage for all species, except for *Salvia*, where DLI had no effect. Node number below the first open flower in *Salvia*, *Celosia*, and *Impatiens* decreased as initial DLI increased, indicating higher rates of floral development. This indicates that seedlings provided with a high DLI during the plug stage will flower earlier and develop fewer nodes before flower initiation.

Previous studies on DLI during the plug stage have shown a hastening of flowering with an increase in DLI. Begonia semperflorens seedlings, provided with continuous supplemental light at 233 μ mol·m⁻²·s⁻¹ delivered 15 to 25 days after germination showed a decrease in days to transplant and days to flower by ≈ 4 days as compared with plants under 13 μ mol·m⁻²·d⁻¹. However, these results could have been confounded with an increase in temperature (up to 4 °C) under the higher light intensity (Graper and Healy, 1990). Flowering of *Petunia* ×hybrida seedlings grown under higher DLIs was accelerated by ≈14 days (Graper et al., 1990). In our study, DLI treatments increasing from 4.1 to 14.2 mol \cdot m⁻²·d⁻¹ decreased subsequent time to flower in all species, but the magnitude varied among the plants tested (Fig. 4-8A). Tagetes, Celosia, Impatiens, and Salvia flowering was accelerated 19%, 24%, 33%, and 41%, respectively, as initial DLI treatments increased from 4.1 to 14.2 mol·m⁻²·d⁻¹. Viola flowering was hastened by 28% as DLI increased from 4.1 to 11.5 mol·m⁻²·d⁻¹. Most of the observed differences in time to flower can be attributed to DLI, as actual temperatures were very similar among DLI treatments ($\leq 1^{\circ}$ C).

High quality plugs are those that have a large dry mass per node (i.e. thick stems) and are relatively compact, since limited size and plug strength are important for shipping and ease of transplanting. Using this definition for plant quality, at the time of transplant, the quality of all species increased as average DLI increased (Fig. 1A-E). Average dry weight per average node number continued to increase linearly as initial

DLI increased from 4.1 to 14.2 mol·m⁻²·d⁻¹ for all species, except for *Salvia*. *Salvia* continued to increase until it reached a maximum under \approx 12 mol·m⁻²·d⁻¹, which may be a saturating DLI for photosynthesis at ambient CO₂ concentrations and at 21 °C (Fig. 1C). Additionally, increasing DLI decreased height at transplant in *Impatiens* and *Salvia*, resulting in a more compact plug. Statistically DLI was quadratically related to height of *Celosia* and *Tagetes*, but these relationships were determined to be horticulturally insignificant. Thus, this data indicates that supplemental lighting used to increase DLI would increase plug quality and accelerate flowering, at least in the range of DLIs studied.

Flower number at flowering in all species decreased as the initial DLI increased, except for *Tagetes*, in which initial DLI and flower number had no significant relationship (Fig. 4-8C). Because plants grown under lower initial DLI treatments took longer to flower, the plants had a longer duration to harvest light in the subsequent environment. Thus, plants had a longer time to photosynthesize and produce more flowers. There was no significant relationship between initial DLI and flower size in *Viola*, but significant relationships were observed in *Impatiens*, *Salvia*, and *Tagetes*.

Dry weight at flowering was linearly related to DLI in all species; with decreasing initial DLI, dry weight at flowering increased. This also may be explained by the longer duration that plants were in the common environment due to delayed flowering. This finding posed the question of whether the dry weight gain per day to flower was related to the initial DLI treatment. Upon further inspection, decreasing linear trends were observed in *Celosia, Impatiens*, and *Salvia* (Fig. 9), indicating that

as DLI increased during the plug stage, dry weight gain per day to flower decreased. This indicates that plants may allocate more energy into flowers if initially exposed to higher DLIs. Alternatively, plants may have had larger leaves when grown under a low DLI initially, and thus were able to capture more radiation than plants grown under a higher DLI. We did not measure leaf area, so further research is needed to support this hypothesis.

Plant height at flowering decreased linearly with increasing initial DLI in *Celosia, Impatiens*, and *Salvia*. Much of this height difference could be attributed to a corresponding linear decrease in node number. Height differences were not as highly correlated in *Tagetes* and were not significant in *Viola*. Corresponding node number differences were very small in *Tagetes* and not significant in *Viola*.

This study quantifies the consequences of growing seedlings under a range of DLIs. Although final flower number, flower size, dry weight were greater under lower initial DLI, flowering was hastened as DLI increased. Future research to determine how exposure to high DLI at different stages of seedling development influence initial quality and subsequent flowering would be of merit.

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R	Treatment	Average DLI (mol· m ⁻² · d ⁻¹)	Average air temperature °C	Ave	erage shoot-t	ip temperat	ure °C	Average VPD (kPa)
				Salvia	Impatiens	Celosia	Tagetes	-
1	LL	4.5	21.0	21.1	21.7	21.5	20.5	0.6
	ML	7.2	21.4	21.6	21.9	21.6	21.2	0.6
	HL	14.2	21.0	21.3	21.6	21.4	20.7	0.6
2	LL	4.1	20.8	21.6	20.8	21.5	20.6	0.7
	ML	7.1	21.4	21.5	21.9	21.7	21.3	0.6
	HL	12.3	21.4	21.4	21.6	21.1	20.6	0.6

Table 1. Actual environmental conditions inside growth chambers with three daily light integral (DLI) treatments. LL=low light, ML= moderate light, HL= high light, VPD= vapor pressure deficit, R= replication.

Table 2. Comparison of canopy and air temperatures (°C) during a 24-h period in growth chambers.

$\frac{\text{DLI}}{(\text{mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1})}$	Salv	ria	Impat	iens	Celo	sia	Tage	etes	Vio	la
	canopy	air	canopy	air	canopy	air	canopy	air	canopy	air
4.1	22.7	21.1	22.7	21.4	22.3	21.0	21.1	20.7	21.6	21.0
7.1	22.0	21.4	22.6	21.5	21.9	21.6	20.9	21.3	21.4	21.6
12.3	21.9	20.9	22.5	21.0	22.0	21.0	20.7	20.8	21.9	21.0

	Average DLI		
Species	$(mol \cdot m^{-2} \cdot day^{-1})$	Average node number	Average flower size (cm)
Celosia	4.1	4.3	
	4.5	4.6	
	7.1	4.9	
	7.2	5.3	
	12.3	5.0	
	14.2	5.2	
	Significance	***	
	P	***	
	P o turi	**	
Impatiens	<u>- Ouadratic</u> 4.1	4.0	5.0
impunens	4.5	4.7	4.8
	7.1	5.1	4.6
	7.2	5.5	4.6
	12.3	4.9	4.2
	14.2	5.7	4.5
	Significance	***	***
	P.	***	***
	P Curdensia	**	**
Salvia	Ouadratic	2.9	4.1
Satvia	4.5	3	4.0
	7.1	3	4.1
	7.2	3	3.4
	12.3	3	3.8
	14.2	3	3.1
	Significance	NS	***
	Pliner	NS	***
	P Quadratic	NS	NS
Tagetes	4.1	2.8	4.0
Iugeres	4.5	3.1	4.0
	7.1	3.4	4.1
	7.2	4 0	4.4
	12.3	3.1	4.3
	14.2	3.8	4.3
	Significance	***	***
	P	***	***
	P Ouadratic	NS	**
Viola	4.1	3.9	3.1
	4.5	3.8	3.0
	7.1	4.6	3.0
	7.2	5.1	3.2
	12.3	5.3	2.9
	14.2	5.6	3.1
	Significance	***	NS
	P	***	NS
	Postati	***	NS

Table 3. The effect of daily light integral (DLI) during the plug stage on node number at time of transplant (n=16) and on subsequent flower size.

NS, **.*** Nonsignificant or significant at $P \le 0.01$, or 0.001 respectively.

--, Data not recorded.

Figure 1. Relationships between daily light integral and average dry weight per average node number as observed in *Celosia*, *Impatiens*, *Salvia*, *Tagetes*, and *Viola* at time of seedling transplant. Each symbol represents the averages of 16 plants. Equations for regression lines are presented with corresponding r^2 values.


Figure 2. Relationship between daily light integral and average height (cm) as observed in *Celosia*, *Impatiens*, *Salvia*, and *Tagetes* at time of transplant. L = linear and Q = quadratic. NS, *,*** Nonsignificant or significant at $P \le 0.05$ or 0.001, respectively. Equations for regression lines are presented with corresponding r² values.





Figure 3. The relationship between DLI and percent visible flower bud at tranplant in *Impatiens* and *Tagetes*.

Figure 4. The effect of daily light integral during the plug stage on subsequent days to flower, node number, flower number, dry weight (g), and height (cm) in *Celosia*. Error bars represent 95% confidence intervals. L = linear and Q = quadratic. NS,*** Nonsignificant or significant at $P \le 0.001$, respectively. Equations for regression lines are presented with corresponding r^2 values



Figure 5. The effects of daily light integral during the plug stage on subsequent days to flower, node number, flower number, dry weight (g), and height (cm) in *Impatiens*. Error bars represent 95% confidence intervals. L= linear and Q= quadratic. NS, *, *** Nonsignificant or significant at $P \le 0.05$, 0.001, respectively. Equations for regression lines are presented with corresponding r² values



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Figure 6. The effects of daily light integral during the plug stage on subsequent days to flower, node number, flower number, dry weight (g), and height (cm) in Salvia. Error bars represent 95% confidence intervals. L = linear and Q = quadratic. NS, *** Nonsignificant or significant at $P \le 0.001$. Equations for regression lines are presented with corresponding r² values.



Figure 7. The effects of daily light integral (DLI) during the plug stage on subsequent days to flower, node number, flower number, dry weight (g), and height (cm) in *Tagetes*. Error bars represent 95% confidence intervals. L= linear and Q= quadratic. NS, *, **, *** Nonsignificant or significant at $P \le 0.05$, 0.01, or 0.001, respectively. Equations for regression lines are presented with corresponding r² values.



Figure 8. The effects of daily light integral during the plug stage on subsequent days to flower, node number, flower number, dry weight (g), and height (cm) in Viola. Error bars represent 95% confidence intervals. L= linear and Q= quadratic. NS, **, *** Nonsignificant or significant at $P \le 0.01$ or 0.001, respectively. Equations for regression lines are presented along corresponding r² values.



Figure 9. The effects of daily light integral during the plug stage on subsequent dry weight gain per day to flower in *Celosia*, *Impatiens*, *Salvia*, and *Tagetes*. Error bars represent 95% confidence intervals. L= linear and Q= quadratic. NS, **, *** Nonsignificant or significant at $P \le 0.01$ or 0.001, respectively. Equations for regression lines are presented with corresponding r² values.



