High Tunnel versus Climate-controlled Greenhouse: Transplant Time and Production Environment Impact Growth and Morphology of Cold-tolerant Bedding Plants

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Abstract. Commercial bedding plant production in northern latitudes often begins in late winter and continues through spring, when average outdoor temperatures require growers to actively heat their greenhouses (GHs). High tunnels (HTs) offer energy savings as they are passively heated and cooled structures that have a low initial cost. As a result, they have been used in northern latitudes to advance and extend the growing season and improve the quality of high-value horticultural crops. However, there is limited published information on growing bedding plants in HTs in northern latitudes. Our objectives were to quantify the effects of transplant date in an HT with or without a rowcover (RC) compared with a traditional heated GH on the growth and morphology of three cold-tolerant bedding plant species at two northern latitude locations, Purdue University (Purdue) and Cornell University (Cornell). Seedlings of snapdragon (*Antirrhinum majus* L. ‘Liberty Classic Yellow’), dianthus (*Dianthus chinensis* L. ‘Telstar Crimson’), and petunia (*Petunia* × *hybrida* Vilm.-Andr. ‘Wave Pink’) were transplanted on weeks 13, 14, and 15 in 2012 (Purdue) and 2013 (both locations) and moved to either a glass-glazed GH or an HT without (HT) or with a rowcover (HT+RC). Several quality measurements increased when plants were grown in the HT compared with those grown in the GH. Dianthus and petunia transplanted at Purdue during week 13 in the HT and HT+RC were 33% and 47% shorter and had 51% and 31% more visible buds, respectively, compared with those grown in the GH. Similarly, petunia transplanted at Cornell during week 13 in the HT and HT+RC were 45% and 43% shorter, respectively, than their GH counterparts. The shoot dry mass of dianthus and snapdragon at Purdue was significantly higher when grown in the HT compared with the GH, regardless of transplant week or the use of RC likely because of increased daily light integral (DLI) in the HT environment. There was about a 1-week delay from transplant to first open flower for week 13 dianthus (at Purdue) and petunia (at both locations) when finished in the HT or HT+RC vs. their GH counterparts. Such a delay would be acceptable to growers who want to reduce the use of chemical growth regulators and heating costs. However, at both locations snapdragon transplanted on week 13 to the HT or HT+RC environments were delayed by 22 to 26 days compared with the GH. A delay of over 3 weeks could interfere with a grower’s production schedule, possibly making this crop unsuitable for production in northern latitude HTs.

Annual bedding plants are the most valuable sector of the commercial floriculture industry, accounting for 62% of the reported wholesale value of \$5.9 billion in the United States (USDA, 2014). Commercial GH production in northern latitudes begins in late winter and continues through spring, when the crops are marketed to consumers. In temperate climates, outdoor temperatures during production necessitate protected cultivation with active heating to prevent crops from freezing and to ensure that growers meet specific market dates. However, with the relatively volatile prices for propane, heating oil,

and natural gas during the last decade, heating now accounts for 10% to 30% of the total operating costs for commercial GHs (Brumfield, 2009; EIA, 2014; Langton et al., 2006). To reduce costs associated with heating, growers have installed thermal energy curtains, increased insulation, switched to alternative fuel sources, and purchased energy-efficient heaters (Blanchard and Runkle, 2011a). Some growers in northern latitudes are starting to grow bedding plants in HTs to further reduce or eliminate heating costs (Steve Hood, personal communication). Additionally, HTs can provide warmer day temperatures and protection

from rain as compared with plants growing in an outdoor environment. However, there is limited published information regarding bedding plant production in HTs.

A HT typically is a single-layer, polyethylene-covered structure that lacks automated ventilation, is heated by solar radiation, and is cooled through side or end walls that are manually opened and closed (Lamont, 2009). They are primarily used in temperate northern latitudes to extend the production season and improve the quality of high-value horticultural crops, including vegetables, fruits, and cut flowers (Hunter et al., 2012; Knewtson et al., 2010; Lamont, 2005; Ortiz et al., 2012; Rowley et al., 2010). Additionally, they are used in temperate and tropical regions of the world to exclude rain from crops, which reduces disease pressure and crop loss (Lamont, 2009). Recent research has shown that growers can use HTs to reduce or eliminate heating costs associated with finishing cold-tolerant bedding plants in northern latitudes (Currey et al., 2014).

Greenhouse growers use average daily temperature (ADT) to predict when crops will be marketable (Blanchard and Runkle, 2011a). It is well documented that temperature controls the rate of plant development, including time to unfold a leaf and time to first open flower (Adams et al., 1998; Kaczperski et al., 1991; Roberts and Summerfield, 1987). Plant development is zero at or below a species-specific base temperature (T_b). As temperatures increase above T_b , the rate of development increases until the optimum temperature (T_o) is reached. For many crops, the development rate increases nearly linearly with ADT between T_b and T_o (Blanchard and Runkle, 2011a; Roberts and Summerfield, 1987). This linear relationship enables growers to predict when crops will be marketable based on the ADT. Consequently, a grower’s ability to predict when their crops will be ready for market is not possible in an HT due to lack of temperature control. Notwithstanding this limitation, in some situations, the energy savings of reduced or no heating associated with HT bedding plant production can still outweigh the ability to schedule crops for specific market dates (Currey et al., 2014).

A comparison of finishing spring bedding plants transplanted during week 14 in HTs to a GH revealed that dianthus (*D. chinensis*), petunia (*Petunia* × *hybrida*), and pansy (*Viola* × *cornuta*) could be produced in an HT with little to no delay in time to flower. For example, dianthus, petunia, and pansy grown in an HT were delayed by as few as 4, 4, and 0 d, respectively, compared with a GH (Currey et al., 2014). However, a –6 °C night resulted in the death of several cold-sensitive and cold-intermediate species. This revealed the potential risk associated with the production of spring bedding plants in HTs. Since several cold-tolerant species survived the cold night and were only slightly delayed in flowering time, we investigated the effects of transplant week to determine if earlier transplant times were possible. To our knowledge, no work has been performed to determine the effects of early-season transplant (weeks 13 to 15) of

cold-tolerant bedding plants in unheated HTs located in temperate northern latitudes. Also, we postulated that a RC could reduce the impact of low temperatures, as demonstrated by Currey et al. (2014). Therefore, the objectives of this study were to quantify the effect of three transplant dates in two northern latitudes, the use of a RC, and holding plants in a heated GH before moving them to an HT on the growth and development of three cold-tolerant bedding plant species.

Materials and Methods

Expt. 1

Plant material and culture. Seedlings of snapdragon (*A. majus* L. 'Liberty Classic Yellow'), dianthus (*D. chinensis* L. 'Telstar Crimson'), and petunia (*Petunia ×hybrida* Vilm.-Andr. 'Wave Pink') in 288-cell (6-ml individual cell volume) plug trays were obtained from a commercial GH propagator (C. Raker and Sons, Litchfield, MI). The plant material was received at Purdue University (Purdue) in West Lafayette, IN (40 °N latitude) in 2012 on 27 Mar. (week 13), 3 Apr. (week 14), and 10 Apr. (week 15) and in 2013 at both Purdue and Cornell University [Cornell, Ithaca, NY (42 °N latitude)] on 28 Mar. (week 13), 4 Apr. (week 14), and 11 Apr. (week 15). The experiments at Purdue and Cornell are denoted as Expts. 1A and 1B, respectively. On each receiving date, 21 seedlings of each species were transplanted into 10-cm-diameter (480 mL) round containers filled with a commercial soilless medium comprised of (by vol.) 65% peat, 20% perlite, and 15% vermiculite (Fafard 2; Fafard, Inc., Agawam, MA). Plants were hand irrigated as necessary with water supplemented with water-soluble fertilizer (Peters Excel® 21-5-20; Everris NA Inc., Marysville, OH) to provide (in mg·L⁻¹) 200 nitrogen (N), 26 phosphorus (P), 163 potassium (K), 1.0 iron (Fe), 0.5 manganese (Mn) and zinc (Zn), 0.24 boron (B) and copper (Cu), and 0.1 molybdenum

(Mo). At Purdue irrigation water was supplemented with 93% sulfuric acid (Ulrich Chemical, Indianapolis, IN) at 0.08 mg·L⁻¹ to reduce alkalinity to ≈100 mg·L⁻¹. At Cornell, no acid supplementation was used, tap water alkalinity was ≈115 mg·L⁻¹.

Greenhouse environment. Seven plants of each species were randomly selected during each transplant week, spaced equally in trays, and placed on benches located in a glass-glazed GH under natural photoperiods and a constant air temperature set point of 21 °C. Temperature was maintained with exhaust fan and evaporative-pad cooling, radiant hot-water heating, and retractable shade curtains controlled by environmental computers (Maximizer Precision 10; Priva Computers Inc., Vineland Station, Ontario, Canada) and (Operator Program; Argus Control Systems, White Rock, British Columbia, Canada) at Purdue and Cornell, respectively.

High tunnel environment. Seven plants of each species were randomly selected during each transplant week, spaced equally in trays, and placed in an HT on top of a layer of landscape fabric. At Purdue, the east-west-oriented HT (14.6 × 7.9 × 3.7 m high) had a triple galvanized structural steel frame (FarmTek, Dyersville, IA) and 6-mm Sun-Master polyethylene film containing copolymer resin with trilayer construction and ultraviolet additives (Lumite, Baldwin, GA) and was located in Lafayette, Indiana (40 °N). At Cornell, the east-west oriented HT (29.3 × 9.1 × 4.6 m high, Rimol Greenhouse Systems, Hooksett, NH) was glazed with a 6-mm clear ultraviolet-treated polyethylene film. At both locations, the HT was split into two production environments: one with a rowcover (HT+RC) and another without a rowcover (HT). At Purdue, end-wall peak vents, end-wall doors, and roll-up side walls were opened or closed manually to moderate temperature swings. End-wall peak vents were opened when the forecast high was >13 °C, end-wall vents and doors were opened when the forecast high was >21 °C, and vents, doors, and roll-up side walls were opened when the forecast high was >24 °C. All ventilation was closed during periods of high winds and/or low temperatures. At Cornell, side wall ventilation was thermostat-controlled using a battery-powered motor to roll up side walls (to a 1.2 m height) when temperature inside the HT was above 29 °C or roll down when HT temperature fell below 18 °C. In addition, end-wall peak vents and doors were manually opened in mid-to-late spring when outdoor day temperatures greater than 21 °C were anticipated. On nights when the forecast low was <3 or <5 °C, a high-density polyethylene fabric RC (Covertor Pro 19 floating rowcover; Fiberweb, London, UK) or (Agribon+ AG-19; Agribon, San Luis Potosi, Mexico) was pulled over a 45-cm-tall frame made of PVC at Purdue and Cornell, respectively, with the other half of the plants not being covered with fabric. At Cornell, when subsequent outdoor day temperatures were forecast to be <12 °C the RC was kept on during the day.

Expt. 2

This experiment used the same plant material, cultural practices, and production environments described in Expt. 1. Twenty-eight seedlings of each species were transplanted in the GH on 28 Mar. 2013 (week 13) at both Purdue (Expt. 2A) and Cornell (Expt. 2B). Seven plants remained in the GH for the duration of the experiment with the remaining plants being moved to the HT on 28 Mar. (week 13), 4 Apr. (week 14), and 11 Apr. 2013 (week 15) after being held in the GH environment for 0, 1, and 2 weeks, respectively.

Environmental data collection. At Purdue, HT air temperature and light intensity were measured at 20-s intervals with an enclosed thermocouple and quantum sensor, respectively, placed at plant height (Watch-Dog Model 2475 Plant Growth Station; Spectrum Technologies, Inc., Plainfield, IL). Air temperature in the Purdue GH was monitored and recorded with the Priva environmental computer. Two quantum sensors (Model SQ-212; Apogee Instruments, Inc., Logan, UT) placed at plant height measured light intensity every 30 s and the average of each sensor was logged every 15 min by a data logger (Watch-dog 2800 Weather Station, Spectrum Technologies). A conversion factor was calculated to calibrate the quantum sensors used in the HT to those used in the GH. At Cornell, HT air temperature and light intensity were measured at 60-s intervals with an enclosed thermocouple and quantum sensor and averaged and logged every 10 min by a data logger (HOB0 U12-012; Onset Computer Corp., Bourne, MA) placed at plant height. In the GH at Cornell, line quantum sensors (SQ-316, Apogee Instruments, Inc., Logan, UT) were placed at plant height to record light intensity. Air temperature and light intensity were recorded every 10 s and averages were logged every 10 min by a data-logger (CR3000; Campbell Scientific Inc., Logan, UT). Average daily, minimum, and maximum temperatures and DLI for each month of the study are reported in Tables 1 and 2.

Data collection and calculations. Plants were monitored daily and the date of first open flower was recorded to determine the number of days from transplant to flower (TTF). At flowering, stem length was measured as the distance from the medium surface to the growing tip of the longest shoot, and total visible flower buds were recorded. For snapdragon, each inflorescence was recorded as a flower. Plants were destructively harvested at the medium surface, dried in an oven at 70 °C for 1 week, and shoot dry mass was determined.

Experimental design and statistical analyses. Both experiments were laid out in a completely randomized design in a factorial arrangement. The factors for Expt. 1 were production environment (three levels) and transplant date (three levels). The factors for Expt. 2 were production environment (three levels) and weeks held in GH (three levels). Several experimental conditions were different between Purdue and Cornell, therefore,

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Table 1. *Purdue University*. Mean daily light integral (DLI), minimum and maximum temperature, and average daily temperature (ADT) for bedding plants grown in a climate controlled greenhouse (GH) or high tunnel (HT) with (HT+RC) or without rowcover in 2012 and 2013. Data are means ($\pm$ SD) of average values recorded every 10 or 15 min.

Month	ADT (°C)			Temperature (°C)						DLI (mol·m ⁻² ·d ⁻¹)			
				Minimum			Maximum						
	GH	HT	HT+RC	GH	HT	HT+RC	GH	HT	HT+RC	GH	HT	HT+RC	
2012													
March	21.2 (± 0.6)	17.5 (± 4.9)	17.4 (± 5.1)	20.3 (± 0.2)	7.3 (± 2.2)	7.3 (± 2.2)	22.6 (± 0.5)	38.1 (± 6.1)	38.7 (± 6.2)	9.4 (± 2.2)	24.4 (± 7.4)	21.7 (± 6.8)	
April	21.3 (± 0.7)	14.7 (± 3.2)	15.1 (± 3.0)	20.3 (± 0.4)	5.2 (± 4.5)	6.1 (± 3.7)	22.7 (± 0.7)	29.6 (± 5.5)	30.7 (± 6.8)	10.6 (± 2.7)	26.5 (± 8.6)	22.1 (± 6.8)	
May	22.4 (± 1.9)	21.0 (± 4.1)	20.9 (± 4.1)	20.7 (± 0.5)	13.3 (± 5.1)	13.2 (± 5.1)	25.1 (± 2.5)	29.9 (± 5.1)	30.1 (± 4.5)	12.9 (± 2.9)	32.9 (± 6.7)	32.3 (± 6.9)	
June	22.2 (± 1.8)	19.7 (± 3.8)	19.7 (± 3.8)	20.7 (± 1.0)	11.6 (± 3.1)	11.6 (± 3.1)	24.9 (± 2.3)	27.8 (± 4.7)	27.8 (± 4.7)	11.5 (± 1.7)	33.8 (± 8.9)	33.9 (± 8.9)	
2013													
March	21.0 (± 0.5)	14.9 (± 1.6)	15.8 (± 1.6)	19.8 (± 0.3)	0.6 (± 2.9)	2.2 (± 4.6)	22.1 (± 0.6)	40.9 (± 3.1)	43.0 (± 5.2)	12.1 (± 1.4)	25.2 (± 3.5)	23.7 (± 6.8)	
April	21.0 (± 0.7)	14.7 (± 3.7)	15.3 (± 3.5)	19.9 (± 0.4)	5.6 (± 4.9)	6.5 (± 4.1)	22.2 (± 0.8)	30.0 (± 7.7)	31.5 (± 9.3)	10.9 (± 2.6)	21.8 (± 11.0)	21.3 (± 11.1)	
May	22.4 (± 1.8)	19.5 (± 4.7)	19.3 (± 4.1)	20.5 (± 0.8)	12.6 (± 5.7)	12.6 (± 5.5)	24.5 (± 2.3)	28.8 (± 4.5)	28.5 (± 4.7)	12.4 (± 2.7)	25.7 (± 9.5)	27.0 (± 10.5)	
June	21.1 (± 4.0)	17.9 (± 2.4)	17.9 (± 2.1)	20.4 (± 0.1)	11.3 (± 4.0)	11.2 (± 4.0)	23.0 (± 0.7)	26.9 (± 3.9)	26.1 (± 2.7)	13.6 (± 3.4)	28.9 (± 14.4)	32.1 (± 16.1)	

Table 2. *Cornell University*. Mean daily light integral (DLI), minimum and maximum temperature, and average daily temperature (ADT) for bedding plants grown in a climate controlled greenhouse (GH) or high tunnel (HT) with (HT+RC) or without RC in 2013. Data are means ($\pm$ SD) of average values recorded every 10 or 15 min.

Month	Temperature (°C)									DLI (mol·m ⁻² ·d ⁻¹)		
	ADT (°C)			Minimum			Maximum					
	GH	HT	HT+RC	GH	HT	HT+RC	GH	HT	HT+RC	GH	HT	HT+RC
2013												
March	21.4 (± 0.2)	10.5 (± 3.3)	12.7 (± 5.0)	20.7 (± 0.1)	-0.8 (± 1.7)	0.8 (± 1.9)	22.8 (± 0.2)	32.2 (± 9.6)	38.0 (± 13.4)	12.0 (± 4.2)	15.1 (± 6.1)	9.5 (± 3.8)
April	21.6 (± 0.3)	15.1 (± 4.0)	16.0 (± 4.3)	20.7 (± 0.1)	3.0 (± 4.8)	4.3 (± 4.9)	22.9 (± 0.4)	37.7 (± 8.3)	39.0 (± 11.5)	14.3 (± 4.9)	17.8 (± 4.9)	13.9 (± 4.9)
May	22.3 (± 0.8)	21.6 (± 5.2)	21.8 (± 5.4)	20.6 (± 0.7)	9.7 (± 5.2)	9.8 (± 5.3)	24.0 (± 1.6)	37.9 (± 9.3)	38.8 (± 10.0)	18.0 (± 4.0)	19.9 (± 5.7)	19.1 (± 6.2)
June	22.5 (± 1.1)	22.0 (± 5.3)	22.2 (± 5.3)	21.0 (± 0.5)	12.1 (± 4.9)	12.3 (± 4.9)	24.2 (± 2.3)	38.8 (± 13.0)	39.8 (± 14.1)	15.9 (± 7.6)	22.1 (± 2.7)	20.7 (± 2.6)

data were not pooled and are reported as separate experiments. At Purdue, Expt. 1A was repeated once over time for a total of two experimental runs and data were pooled across time. Effects of production environment, transplant date, and weeks held in the GH were compared by ANOVA using SAS (SAS version 9.3; SAS Institute, Cary, NC) PROC MIXED, with an additional program (Arnold M. Saxton, University of Tennessee, Knoxville, TN) that provided pairwise comparisons between treatments using Tukey's honestly significant test at $P \leq 0.05$.

Results and Discussion

Effect of production environment and RC on temperature and light levels. The conventionally heated GH had a higher ADT than the HT, especially early in the experiment (Tables 1 and 2). For example, the ADTs in the HT and HT+RC were $\approx 6^{\circ}$ C lower than in the GH in March and April for both years at Purdue (Table 1) and in April 2013 at Cornell (Table 2). However, the HT+RC maintained a higher ADT ($\approx 1.5^{\circ}$ C) than in the HT alone during the months when the forecast lows were $< 3^{\circ}$ C. At Purdue, temperatures within the HT were never below 0° C during either year of the study (Table 1). At Cornell, a temperature of -0.8° C was observed in Mar. 2013, whereas the HT+RC treatment was 1.6° C warmer (Table 2). No symptoms of cold/chilling injury were observed in any plants, likely because cold-tolerant species were grown in this study. If temperatures had dropped even further, a temperature increase of 1 to 2° C provided from the RC may have significantly reduced cold injury or crop losses such as those reported in an HT by Currey et al. (2014).

At Purdue, the DLI in the HT and HT+RC was nearly twice as high as in the glass-glazed GH (Table 1) due to the single layer of polyethylene film and limited structural support. The Purdue GH had a significant amount of superstructure that reduced light levels. Additionally, a retractable shade curtain ($\approx 50\%$) was used to maintain the GH set point air temperatures, which also significantly reduced light levels. At Cornell, the HT DLI was only about 25% greater than the GH as the HT polyethylene was 9 years old. Additionally, the GH at Cornell had less structural shading components than the Purdue GH. The DLI in the HT+RC was somewhat reduced compared with the HT at both locations. At Purdue, the RC remained over the plants until 0900 HR, which reduced the DLI by $\approx 8\%$ during Mar. 2012 and 2013. At Cornell, the RC was kept over the plants when cool days ($< 12^{\circ}$ C) followed cool nights. Therefore, the RC was used for 3 (out of 4), 13, 4, and 1 nights in March, April, May, and June, respectively. Consequently, DLI in Cornell HT+RC was reduced by $\approx 20\%$ compared with HT.

Effects of production environment and transplant week on finish time. Expt. 1. At Purdue, transplant week and production environment significantly influenced TTF of all species (Table 3). For instance, TTF of dianthus

and petunia was delayed by 8 d in the HT and HT+RC, compared with plants in the GH, respectively, when transplanted in late March (week 13) and by 4 and 2 d for petunia transplanted in early April (week 14).

At Cornell, transplant week and production environment significantly influenced TTF of petunia and snapdragon, but only transplant week affected TTF for Dianthus (Table 4). Time to flower of dianthus was not significantly affected by production environment but was delayed by 8 to 10 d for transplant week 13 as compared with transplant week 15 (Table 4). The delay may be due to lower DLI in both the GH and HT environments in the early spring. For example, at Cornell, petunia transplanted on week 13, were delayed by 7 to 8 d when finished in the HT and HT+RC environments as compared with the GH (Table 4). For petunia, the delay in TTF for plants in the HT was reduced by later transplants dates. At both locations, snapdragon TTF was delayed in both the HT and HT+RC when transplanted in weeks 13, 14, and 15. For transplant week 13, TTF of HT or HT+RC snapdragon was delayed by 22 to 26 d as compared with the GH. The delay in snapdragon TTF in the HT and HT+RC environments decreased somewhat by later transplant dates, but was still 12 to 14 d for transplant week 15.

Bedding plants are usually considered marketable when at least one flower or inflorescence is fully reflexed (Heins et al., 2000). As stated earlier, the rate of development increases nearly linearly as ADT increases. Petunia transplanted in weeks 13, 14, and 15 in the GH with an ADT $\approx 21^{\circ}\text{C}$ and a DLI of 10 to 12 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ had a fully reflexed flower in ≈ 37 d (Table 3). Developmental rate models for petunia 'Wave Purple' and 'Bravo Blue' have been calculated to predict TTF (Blanchard et al., 2011; Vaid and Runkle, 2013). The authors reported that petunia 'Wave Purple' grown with an ADT of 21°C and a DLI of 10 to 12 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ would flower in ≈ 33 d (Blanchard et al., 2011). Vaid and Runkle (2013) reported that petunia 'Bravo Blue' grown with an ADT of 21°C and an average DLI of 18 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ would flower in ≈ 34 d. This validates that while there is a difference of ≈ 3 d between studies, our GH-grown petunia flowered near the predicted values. At Purdue, petunia transplanted in the HT in weeks 14 and 15 with ADTs of 16 and 17°C and a DLI of 21 and 22 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ flowered in 40 and 37 d, respectively (Table 3). Blanchard et al. (2011) also reported that as DLI increased from 4 to 14 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, TTF of petunia 'Wave Purple' grown at an ADT of 20°C was reduced 12 d. In our study, the DLI in the HT exceeded the maximum DLI presented in the Blanchard et al. (2011), which did not allow us to compare our results to their model. However, the similar TTF for petunia transplanted on week 15 in the GH and HT was likely influenced by the higher DLI in the HT.

Effects of holding in the greenhouse on finish time. Expt. 2. At both Purdue and Cornell holding dianthus in the GH at 21°C

Table 3. *Expt. 1A Purdue University.* Time to flower (TTF; days) from transplant to first open flower for dianthus, petunia, and snapdragon grown in three production environments; greenhouse (GH), high tunnel (HT), high tunnel + rowcover (HT+RC), transplanted during weeks 13, 14, and 15. Means sharing a letter are not statistically different by Tukey's honestly significant difference test at $P \leq 0.05$.

Transplant week (TW)	Production environment (PE)		
	GH	HT	HT+RC
	<i>Dianthus</i>		
Week 13	46 a ^a B ^y	54 aA	54 aA
Week 14	46 aA	48 bA	48 bA
Week 15	43 aAB	43 cB	46 bA
Significance			
TW		***	
PE		***	
TW $\times$ PE		***	
	<i>Petunia</i>		
Week 13	37 aB	45 aA	45 aA
Week 14	37 aB	40 bA	39 bA
Week 15	36 aA	37 cA	38 bA
Significance			
TW		***	
PE		***	
TW $\times$ PE		***	
	<i>Snapdragon</i>		
Week 13	43 aC	69 aA	65 aB
Week 14	42 aB	59 bA	59 bA
Week 15	39 bB	53 cA	52 cA
Significance			
TW		***	
PE		***	
TW $\times$ PE		***	

^aWithin-column means followed by different lower-case letters are significantly different by Tukey's honest significant difference (HSD) test at $P \leq 0.05$.

^yWithin-row means followed by different upper-case letters are significantly different by Tukey's HSD test at $P \leq 0.05$.

***Significant at $P \leq 0.001$.

Table 4. *Expt. 1B Cornell University.* Time to flower (TTF; days) from transplant to first open flower for dianthus, petunia, and snapdragon grown in three production environments; greenhouse (GH), high tunnel (HT), high tunnel + rowcover (HT+RC), transplanted during weeks 13, 14, and 15. Means sharing a letter are not statistically different by Tukey's honestly significant difference test at $P \leq 0.05$.

Transplant week (TW)	Production environment (PE)		
	GH	HT	HT+RC
	<i>Dianthus</i>		
Week 13	54 a ^a A ^y	55 aA	56 aA
Week 14	51 abA	51 abA	50 abA
Week 15	46 bA	47 bA	45 bA
Significance			
TW		***	
PE		NS	
TW $\times$ PE		NS	
	<i>Petunia</i>		
Week 13	44 aB	51 aA	52 aA
Week 14	41 aB	46 bA	47 bA
Week 15	40 aB	44 bAB	45 bA
Significance			
TW		***	
PE		***	
TW $\times$ PE		NS	
	<i>Snapdragon</i>		
Week 13	50 aB	72 aA	74 aA
Week 14	47 abB	65 bA	66 bA
Week 15	45 bB	57 cA	58 cA
Significance			
TW		***	
PE		***	
TW $\times$ PE		***	

^aWithin-column means followed by different lower-case letters are significantly different by Tukey's honest significant difference (HSD) test at $P \leq 0.05$.

^yWithin-row means followed by different upper-case letters are significantly different by Tukey's HSD test at $P \leq 0.05$.

***Significant at $P \leq 0.001$, NS=nonsignificant at ($P > 0.05$).

1 or 2 weeks before moving to the HT or HT+RC did not significantly influence TTF compared with plants moved to the HT or HT+RC directly after transplant (Figs. 1A

and 2A). For petunia placed in the HT, TTF was delayed by ≈ 8 d at both locations compared with plants grown in the GH regardless if they were held in the GH for 0, 1,

Fig. 1. Expt. 2A Purdue University. Time to flower (days), stem elongation (cm), shoot dry mass (g), and visible flower bud number (no.) for dianthus, petunia, and snapdragon grown in three production environments; greenhouse (GH), high tunnel (HT), high tunnel + rowcover (HT+RC), held in the GH for 0, 1, and 2 weeks. Means sharing a letter are not statistically different by Tukey's honestly significant difference test at $P \leq 0.05$, error bars indicate $\pm$ SE.

or 2 weeks (Figs. 1B and 2B). However, holding petunia in the greenhouse for 1 week (Purdue) or 2 weeks (Cornell) reduced TTF by ≈ 5 d as compared with plants held for 0 weeks if they were transplanted in the HT+RC. At both locations, snapdragon transplanted into the HT and HT+RC after 0 weeks in the GH was delayed by 22 to 25 d, compared with those grown in the GH (Figs. 1C and 2C). At Purdue, holding snapdragon in the GH for 1 or 2 weeks reduced the delay in TTF for the HT or HT+RC plants as compared with those held for 0 weeks before moving to the HT environment (Fig. 1C). There was some evidence for this pattern at Cornell but the reduction in TTF was not statistically significant (Fig. 2C). The modest reductions in TTF for petunia and snapdragon may not justify the added energy inputs needed to heat the GH for 1 or 2 weeks, making this production strategy of holding plants in the GH for early establishment in the HT not beneficial for energy savings. However, the overall response in both experiments

reinforces the paradigm that TTF is a function of ADT, assuming other cultural and environmental factors are not limiting (Roberts and Summerfield, 1987).

Effects of transplant week and production environment on growth and morphology. Bedding plants are considered high-quality when they are compact (i.e., reduced stem elongation), fill the container (i.e., high shoot dry mass), are well branched, and have a high flower-bud count (Faust, 2011). Growers generally use chemical growth regulators to manage stem elongation to keep bedding plants compact; however, their use increases production costs. Temperature is another tool that growers can use to manipulate plant morphology to reduce stem elongation. In many plant species, stem elongation is influenced by the difference between the day and night temperatures, or DIF. Stem elongation is promoted when day temperatures are warmer than night temperatures (+DIF) and suppressed when day temperatures are cooler than night temperatures

(-DIF) (Erwin et al., 1989; Erwin and Hines, 1995; Kaczperski et al., 1991). The effects of cooler day temperatures to create a -DIF are generally perceived by plants ≈ 30 min before sunrise until about three hours after sunrise. This response has enabled growers to use a strategy called morning DIP or DROP. A DROP lowers the air temperature set point in the early morning period to simulate a cooler day, then raise the temperature in the late morning to increase the ADT (Blanchard and Runkle, 2011a).

In our study, stem elongation was often significantly less when plants were grown in the HT and HT+RC compared with the GH. Petunia at both locations, dianthus at Purdue, and snapdragon at Cornell had reduced stem elongation in the HT and HT+RC environments as compared with their GH counterparts. For example, petunia transplanted at Purdue during week 13 in the HT and HT+RC were 47% and 43% shorter, respectively, than those in the GH (Fig. 3B). Similarly, petunia transplanted at Cornell during week 13 in the

Fig. 2. Expt. 2B Cornell University. Time to flower (days), stem elongation (cm), shoot dry mass (g), and visible flower bud number (no.) for dianthus, petunia, and snapdragon grown in three production environments; greenhouse (GH), high tunnel (HT), high tunnel + rowcover (HT+RC), held in the GH for 0, 1, and 2 weeks. Means sharing a letter are not statistically different by Tukey's honestly significant difference test at $P \leq 0.05$, error bars indicate $\pm$ SE.

HT and HT+RC were 45% and 43% shorter, respectively, than their GH counterparts (Fig. 4B). At Purdue, dianthus transplanted during week 13 in the HT and HT+RC were 33% and 35% shorter, respectively, than those in the GH (Fig. 3A). At Cornell, snapdragon stem elongation was reduced by about 30% when plants were grown in the HT or HT+RC as compared with the GH regardless of transplant week (Fig. 4C).

In some cases stem elongation was significantly influenced by transplant week. Transplant week had a significant impact on stem elongation in the GH for dianthus and petunia at Purdue. Specifically, dianthus transplanted during week 15 were 12% shorter than those transplanted during week 13, and petunia transplanted during week 15 were 12% shorter than those transplanted during week 14 (Fig. 3A and B). At Cornell, HT+RC dianthus transplanted during week 15 were 24% shorter than those transplanted during week 13 (Fig. 4A). Greenhouse petunia at Cornell were 19% shorter

when transplanted at week 14 vs. week 13. The inhibition in stem elongation in the later transplant weeks for dianthus and petunia was likely affected by the increase in DLI as the spring progressed (Tables 1 and 2).

For Expt. 2 at Purdue, HT and HT+RC dianthus and petunia held in the GH for 0, 1, or 2 weeks were significantly shorter than their counterparts finished solely in the GH (Fig. 1D and E). For Expt. 2 at Cornell, dianthus moved to the HT after 2 weeks were significantly shorter than their counterparts finished solely in the GH (Fig. 2D). GH-grown petunia at Cornell were about twice the height as their counterparts finished under HT and HT+RC, regardless of whether they were held in the GH for 0, 1, or 2 weeks (Fig. 2E). Similarly, although the magnitude of stem elongation response was not as large, HT and HT+RC snapdragon were significantly shorter than their GH counterparts (Fig. 2F).

While our results appear to contradict the concept of DIF to control stem elongation it

should be noted that the majority of studies conducted to determine effects of DIF were performed in controlled environments, where temperatures were highly regulated (Erwin et al., 1989; Kaczperski et al., 1991) as compared with the highly variable temperatures in the HT in the present study. We expected the large +DIF in the HT (Table 1) to promote stem elongation. An HT experiences large diurnal temperature fluctuations, which makes it difficult to compare our results to ones that were completed in controlled environments. Currey et al. (2014) reported similar reductions in stem elongation in several HT-grown bedding plant species when compared with that in a conventional GH. Their lowest nighttime temperature generally occurred predawn, and the authors suggested that this temperature regimen may have created a temperature DROP effect, which can create a -DIF response (Currey et al., 2014). We experienced similar trends in our HT and postulate that cool

Fig. 3. Expt. 1A Purdue University. Stem elongation (cm), shoot dry mass (g), and visible flower bud number (no.) of dianthus, petunia, and snapdragon grown in three production environments; greenhouse (GH), high tunnel (HT), high tunnel + rowcover (HT+RC), transplanted during weeks 13, 14, and 15. Means sharing a letter are not statistically different by Tukey's honestly significant difference test at $P \leq 0.05$, error bars indicate $\pm$ SE.

morning temperatures may have led to the suppression in stem elongation of petunia and dianthus grown in the HT.

Additionally, we postulate that suppression of stem elongation in the HT was influenced by the higher DLI. Increasing DLI has been shown to reduce stem elongation, during both constant and diurnal temperatures regimens (Faust et al., 2005; Kaczkowski et al., 1991). For example, plant height of 'Snow Cloud' petunia grown at a constant air temperature of 15 °C was reduced by 32% as DLI increased from 6.5 to 13 mol·m⁻²·d⁻¹. Additionally, plant height for petunia grown with a diurnal day/night temperature of 20/15 °C was reduced by 29% as DLI increased from 6.5 to 13 mol·m⁻²·d⁻¹ (Kaczkowski et al., 1991). Increasing the DLI has also been shown to increase the number of lateral shoots of many bedding plant species (Faust, 2011). We did not quantify the number of lateral shoots, but plants grown in the HT had more lateral branches (data not shown) than those grown in the GH. Increased lateral branching results in a reduction of stem elongation and could further explain the reduced stem elongation in the HT.

It is well established that increasing DLI generally increases biomass accumulation (Faust et al., 2005; Heins et al., 2000; Kaczkowski et al., 1991). High shoot dry mass (along with a compact plant form) is a desirable quality trait as it can serve as one quantitative measure

of how well a plant has "filled out" a container. At Purdue, where the HT and HT+RC environments had much greater DLI than the GH, the shoot dry mass of dianthus and snapdragon was significantly greater when they were grown in the HT and HT+RC compared with the GH, regardless of transplant week. Shoot dry mass was also influenced by transplant week. For example, dianthus at Purdue transplanted in week 13 in the HT and HT+RC had a 27% and 16% increase in shoot dry mass, respectively, than those transplanted in week 15 (Fig. 3D). Additionally, snapdragon transplanted at Purdue during week 13 in the HT and HT+RC had a 37% and 21% increase in shoot dry mass, respectively, than those transplanted in week 15 (Fig. 3F). Similarly at Cornell, HT snapdragon transplanted during week 13 had a 28% increase in shoot dry mass than plants transplanted on week 15 (Fig. 4F).

For Expt. 2 at Purdue, HT and HT+RC dianthus exhibited greater shoot dry mass regardless of whether they were held for 0, 1, or 2 weeks in the GH as compared with their counterparts finished solely in the GH (Fig. 1G). Additionally, snapdragon exhibited a similar positive shoot dry mass response to the HT and HT+RC environment, although the effect was reduced the longer the plants were held in the GH (Fig. 1I). Shoot dry mass of petunia in Expt. 2 at Purdue did not respond to HT or HT+RC treatment (Fig. 1H). At

Cornell, dianthus in Expt. 2 had a greater shoot dry mass than GH only plants when held in the greenhouse for 1 week before moving to HT+RC (Fig. 2G). Petunia in the HT and HT+RC treatment at Cornell had reduced shoot dry mass regardless of whether they were held in the GH for 0, 1, or 2 weeks as compared with their GH only counterparts (Fig. 2H). Shoot dry mass of snapdragon were not significantly affected by HT or HT+RC treatment at Cornell (Fig. 2I).

Plant growth, defined as an irreversible increase in plant size, is a function of biomass production driven by photosynthesis (Heins et al., 2000). Decreased ADT increases time to flower so plants have more time to accumulate light and hence biomass (Blanchard et al., 2011). Therefore, we believe the lengthened production time for some HT plants as well as increased DLI were responsible for the increased shoot dry mass for dianthus and snapdragon (Table 1).

High visible flower bud count is considered one of the primary factors of high-quality associated with marketing bedding plants (Faust, 2011) as visible buds contribute to floral display in the retail/consumer environment. Reduced air temperatures and increased DLI generally increases flower number and size in shade-avoiding plants (Heins et al., 2000). At Purdue, visible bud number was significantly greater in the HT and HT+RC production environments for dianthus and

Fig. 4. Expt. 1B Cornell University. Stem elongation (cm), shoot dry mass (g), and visible flower bud number (no.) for dianthus, petunia, and snapdragon grown in three production environments; greenhouse (GH), high tunnel (HT), high tunnel + rowcover (HT+RC), transplanted during weeks 13, 14, and 15. Means sharing a letter are not statistically different by Tukey's honestly significant difference test at $P \leq 0.05$, error bars indicate $\pm$ SE.

snapdragon transplanted in week 13 and 14 and petunia transplanted week 13 compared with the GH (Fig. 3G–I). For example, visible flower bud number of dianthus increased 51% and 41% in the HT and 54% and 38% in the HT+RC in week 13 and 14, respectively, when compared with the GH (Fig. 3G). However, there were no significant differences for HT and HT+RC production environments transplanted in week 15 compared with those in the GH (Fig. 3G and H). For Purdue snapdragon, visible flower bud number increased 68% and 71% in the HT and HT+RC for plants transplanted in week 13, respectively, when compared with the GH (Fig. 1J). At Cornell, trends in visible flower bud number between GH, HT, or HT+RC were a bit less dramatic, likely due to less differences in DLI than at Purdue (Table 2). At Cornell, HT benefits on visible flower buds was most evident at week 13. At Cornell, HT dianthus transplanted week 13 had a 73% increase in visible flower bud vs. their GH or HT+RC counterparts (Fig. 4G). Snapdragon at Cornell transplanted in week 13 had a 160% increase in visible flower buds when finished in the HT vs. the GH (Fig. 4I).

At Purdue, visible bud number of dianthus in Expt. 2 was significantly greater for HT/HT+RC plants held in the GH for 0 weeks as compared with plants finished solely in the GH (Fig. 1J). Petunia moved to the HT after

0 or 1 weeks or to HT+RC after 1 week had more visible buds than their GH counterparts (Fig. 1K). Similarly snapdragon moved to the HT at 0 or 1 week or to HT+RC after 0 week had more visible buds than plants finished in the GH only (Fig. 1L). At Cornell, dianthus in Expt. 2 that were moved to the HT after 0 week had 64% more visible buds than their GH only counterparts (Fig. 2J). Visible bud of petunia in Expt. 2 were unaffected by HT/HT+RC treatment (Fig. 2K). Snapdragon in Expt. 2 had more visible buds when moved to the HT after 0, 1, or 2 weeks or to HT+RC after 1 or 2 weeks as compared with their GH only counterparts (Fig. 2J).

Collectively our findings indicate that in several cases the cool, high-light environment (Tables 1 and 2) of the HT, whereas delaying TTF, can contribute to higher quality bedding plants by reducing stem elongation, increasing shoot dry mass, and increasing visible flower bud number. Similarly, in a controlled greenhouse experiment number of visible buds at flowering for petunia 'Easy Wave Coral Reef' and 'Wave Purple' increased as ADT was decreased from 26 to 14 °C and DLI increased from 4 to 19 mol·m⁻²·d⁻¹ (Blanchard and Runkle, 2011a). Increased visible flower number may be due, in part, to increased lateral branching under low ADT, as reported for petunia 'Dreams Rose' by Mattson and Erwin

(2003). In several cases, response to production environment differed between the three crops investigated in our study. This was expected as plant growth and TTF response to light and temperature are well known to vary according to plant species and cultivar (Blanchard and Runkle, 2011b; Faust et al., 2005; Mattson and Erwin, 2005).

Conclusion

In summary, our findings demonstrate that cold-tolerant bedding plants can be successfully finished in an HT environment at two different northern latitude locations. Overall, plant quality, in terms of reduced stem elongation and increased shoot dry mass and visible flower bud number, was significantly improved in an HT as compared with the GH although results varied based on species, location, and transplant week. A negative consequence of HT production was delayed flowering especially in snapdragon. Waiting to transplant and move to the HT until weeks 14 or 15 can partially ameliorate the delays in flowering exhibited by plants moved into the HT on week 13. While the RC increased minimum night temperature it did not have a major effect on crop quality, perhaps because extreme low temperature events were not encountered in 2012 or 2013. Holding bedding plants in the

GH before moving to the HT growing environment did not significantly reduce TTF in most cases and thus may not be an energy-efficient practice. While the HT environment can be successfully used to finish high-quality bedding plants, it can be risky due to losses from extreme outdoor temperature fluctuations. Growers can mitigate this risk by holding transplants in a GH temporarily, use of RC, and having emergency heating available.

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