Late-season High Tunnel Planting of Specialty Cut Flowers in the Midwestern United States Influences Yield and Stem Quality

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ADDITIONAL INDEX WORDS. daily light integral, hoop house, field production, stem length

SUMMARY. Production and market value of U.S. grown specialty cut flowers has increased over the past several years due to stem quality issues related to long-distance transport, regional proximity to market centers, and consumer's willingness to purchase locally. Cut flowers are traditionally grown in field or greenhouse environments; however, high tunnels provide an alternative production environment and a number of cultural and economic advantages. Specialty cut flower species 'Campana Deep Blue' bellflower (*Campanula carpatica*), bells of ireland (*Moluccella laevis*), 'Bombay Firosa' celosia (*Celosia cristata*), 'Amazon Neon Purple' dianthus (*Dianthus barbatus*), 'Fireworks' gomphrena (*Gomphrena pulchella*), 'Vegmo Snowball Extra' matricaria (*Tanacetum parthenium*), and 'Potomac Lavender' snapdragon (*Antirrhinum majus*) were planted in both field and high tunnel environments during the late season (early summer) in the midwestern United States. Compared with field production, high tunnel production yielded 9.1 stems/m² (75%) for bells of ireland and 9.5 cm (15%), 16.8 cm (16%), 6.7 cm (44%), and 6.3 cm (19%) longer stems for bells of ireland, celosia, gomphrena, and matricaria, respectively. Additionally, stem length and caliper was greatest for high tunnel-grown bells of ireland, celosia, and dianthus. Our results indicate that late-season planting and production in a high tunnel is suitable for most of the species we investigated.

In years past, production of the major North American cut flower crops [rose (*Rosa* sp.), carnation (*Dianthus caryophyllus*), chrysanthemum (*Chrysanthemum × morifolium*), and alstroemeria (*Alstroemeria* sp.)] were grown primarily in greenhouses for local consumption. However, due to increased energy and labor costs, domestic production of the major cut flowers has shifted to South American or African countries (near the equator) where more ideal year-around production environments and low labor costs exist (Pertwee, 2003; Wien, 2009). The resulting shift led to production

of specialty cut flowers in the United States that are not well adapted to long-distance transportation, and therefore proximity of production to market creates a competitive advantage (Koch, 1996; Ortiz et al., 2012; Wien, 2009; Yue and Hall, 2010).

Although cut flowers were traditionally grown in greenhouses, alternative production methods including field (Starman et al., 1995) and unheated high tunnel (Ortiz et al., 2012; Wells and Loy, 1993; Wien, 2009) production have been investigated. The low cost of growing specialty cut flowers in the field may be appealing, but the risk of extreme weather, seasonal production, and limited environmental control options can be risky (Kelly, 1991; Ortiz et al., 2012). Previous studies have

been conducted to assess annual and perennial field-grown specialty cut flower performance and adaptability to environmental conditions in the southeastern United States (Starman et al., 1995). In addition, Ortiz et al. (2012) compared early- to very late-season planting (late spring to late summer) in a high tunnel to field-grown specialty cut flowers in the midwestern United States.

A high tunnel is a single or multi-span temporary structure made from pipe or other durable framework that is covered with a single or double layer of greenhouse grade 4- or 6-mm plastic and typically has no electrical service, automated ventilation, or heating system (Lamont et al., 2002; Wells, 1996). High tunnels provide a number of advantages for growing cut flowers, including increased soil temperatures in early spring and late fall, season extension, protection from low temperatures in northern climates, and weather phenomena (excessive rain, hail, and wind) (Lamont, 2009; Wien, 2009). Therefore, these relatively calm and protected growing conditions maintain flower quality while also reducing flower disfiguring from disease (Lamont, 2009; Wien, 2009). Additionally, while high tunnels are intended for season extension for spring and fall cut flower production, they are also useful during the summer (Wells and Loy, 1993).

To our knowledge, no studies have been published on late-season planting (summer) in the field and high tunnel of the seven selected specialty cut flower cultivars used in this study in the midwestern United States. These cultivars were selected based on characteristics of cut flower crops suitable for U.S. plant hardiness zone 5b, field and high tunnel production, and popularity among consumers. The objectives of our research were to 1) assess the weekly yield,

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.0254	mil	mm	39.3701
1	ppm	mg·L ⁻¹	1
0.001	ppm	mL·L ⁻¹	1000
(°F–32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

marketable stems, and quality differences of the seven specialty cut flowers in both field and high tunnel production systems; 2) quantify differences between field and high tunnel production systems; and 3) determine which of the species are best suited for late-season cut flower planting in the mid-western United States.

Materials and methods

PLANT MATERIAL AND GREENHOUSE ENVIRONMENT. Between 3 and 6 June 2013, seeds of ‘Campana Deep Blue’ bellflower, ‘Bombay Firosa’ celosia, ‘Amazon Neon Purple’ dianthus, ‘Fireworks’ gomphrena, ‘Vegmo Snowball Extra’ matricaria, and ‘Potomac Lavender’ snapdragon (PanAmerican Seed, West Chicago, IL) were sown. On 19 June, bells of ireland (PanAmerican Seed) seeds were sown. All seeds were sown into 72-cell plug trays (30.7-mL individual cell volume; Landmark Plastics, Akron, OH) filled with a commercial soilless medium composed of (by volume) 65% peat, 20% perlite, and 15% vermiculite (Super Fine Germinating Mix; Sun Gro Horticulture, Agawam, MA) and placed under a natural photoperiod. Bells of ireland, celosia, dianthus, gomphrena, and matricaria seeds were covered with a thin layer of vermiculite (Sunshine, Sun Gro Horticulture) to maintain moisture. Seedlings were irrigated as necessary with acidified water supplemented with 93% sulfuric acid (Ulrich Chemical, Indianapolis, IN) at 0.08 mL·L⁻¹ to reduce alkalinity to ≈ 100 mg·L⁻¹ calcium carbonate and pH to a range of 5.8 to 6.2. After hypocotyl emergence, all seedlings were irrigated as necessary with acidified water supplemented with water-soluble fertilizer (Jack’s LX 16N–0.94P–12.3K Plug Formula for High Alkalinity Water; J.R. Peters, Allentown, PA) to provide (in ppm): 100 nitrogen (N), 10 phosphorus (P), 78 potassium (K), 18 calcium (Ca), 9.4 magnesium (Mg), 0.10 boron (B), 0.05 copper (Cu), 0.50 iron (Fe), 0.25 manganese (Mn), 0.05 molybdenum (Mo), and 0.25 zinc (Zn).

Plant material was maintained in a glass-glazed greenhouse with exhaust fan and evaporative pad cooling, radiant hot-water heating, and retractable shade curtains controlled by an environmental control system (Maximizer Precision 10; Priva Computers, Vineland Station, ON, Canada) at Purdue University, West Lafayette,

IN (lat. 40°N). During the young plant stage, the average greenhouse air temperature and the daily light integral (DLI) were (mean $\pm$ SD) 24.8 $\pm$ 2.4 °C and 19.6 $\pm$ 8.0 mol·m⁻²·d⁻¹, respectively.

FIELD AND HIGH TUNNEL ENVIRONMENTS. Field and high tunnel environments were located at the Meigs Farm, Throckmorton Purdue Agriculture Center, Tippecanoe, IN (lat. 40.29°N, long. 86.88°W). The field plot measured 48 ft long $\times$ 26 ft wide. The high tunnel (48 ft long $\times$ 26 ft wide $\times$ 12 ft tall) was constructed with a triple-galvanized structural steel frame (FarmTek, Dyersville, IA) and covered with 6-mm polyethylene film containing copolymer resin with trilayer construction and ultraviolet additives (SunMaster®; Lumite, Baldwin, GA) that allowed 92% light transmission. Ventilation was provided by manually operated end-wall peak vents and roll-up side walls. Side walls were rolled down as needed during periods of high winds. During periods when air temperature was above 4 °C and winds were calm, the high tunnel doors and vents were left open.

Topsoil in the field environment is from the Drummer soil series (fine-silty, mixed, and mesic Typic Endoaquoll) that typically contains $\approx 3.2\%$ organic matter and has a pH of 7.0. Eight raised beds (40 ft long $\times$ 4 ft wide $\times$ 6 inches tall) were constructed in an east–west orientation, in total, four in the field and four in the high tunnel. All eight beds were amended using pulverized topsoil and compost (Blended Topsoil; Soilmaker, West Lafayette, IN) with a soil pH of 6.6. A drip tape watering system (Aqua-Traxx®; Toro Micro-Irrigation, El Cajon, CA) was installed in each bed at ≈ 1 -ft spacing. Weed barrier fabric was secured down on the beds using landscape anchor pins to reduce weed pressure and maintain soil moisture.

PLANT CULTURE. At transplant, holes were cut out of the weed barrier fabric at recommended crop spacing (PanAmerican Seed, 2013). Celosia seedlings were transplanted into raised beds on 28 June, dianthus and gomphrena on 2 July, matricaria and snapdragon on 9 July, bellflower on 12 July, and bells of ireland on 15 July. Depending on the species, each plot contained ≈ 16 to 81 plants.

At 2 and 10 d after the last transplanting date, white trellis netting (Johnny’s Selected Seeds, Winslow, ME) was secured above the beds at intervals of 8 and 18 inches, respectively, resulting in two layers of plant support. Plants in the field and high tunnel environments were simultaneously irrigated as needed based on visual observation of the plants. At each irrigation event, plants received clear water supplemented with water-soluble fertilizer (Peters Excel® Cal-Mag 21N–2.2P–16.5K; Everris NA, Dublin, OH) to provide (in ppm): 100 N, 10 P, 79 K, 0.5 Fe, 0.12 Cu, 0.12 B, 0.25 Mn, 0.25 Zn, and 0.05 Mo.

ENVIRONMENTAL DATA COLLECTION. For both field and high tunnel environments, an enclosed thermocouple and external quantum sensor recorded air temperature and light intensity, respectively, every 20 s and averages were logged every 15 min by a data logger (WatchDog model 2475 Plant Growth Station; Spectrum Technologies, Aurora, IL). Average air temperature and DLI were calculated for both locations and reported in Table 1.

DATA COLLECTION AND ANALYSIS. The time to harvest (TTH) was recorded as the number of days after transplant until the first stem was harvested for each plot. All plants within each block were used in recording the total number of marketable stems, the total number of stems harvested per week, and the duration of the harvest period. Ten stems of each species were selected at random from each block to determine the following quality measurements: stem length and caliper, and flower number, length, and width. Stem marketability was determined by length (greater than 30 cm) and flower quality (no visual defects). Stems shorter than 30 cm and stems with damaged or disfigured flowers were deemed unmarketable. Stem caliper was measured 3 cm above the harvest cut with a digital caliper (digiMax; Wiha, Schonach, Germany). Depending on species, flower number was determined by counting individual cockscombs (celosia), flower buds showing visible color, open, and fully reflexed flowers (bellflower, dianthus, gomphrena, matricaria, and snapdragon), or calyces (bells of ireland). With the exception of celosia, flower length and width was determined by measuring the length

Table 1. Summer (1 July to 31 Aug.) and fall (1 Sept. to 18 Oct.) growing period, air temperature, and daily light integral (DLI) for bellflower, bells of ireland, celosia, dianthus, gomphrena, matricaria, and snapdragon cut flowers grown in a field or high tunnel at Meigs Farm (Tippecanoe, IN) in 2013. Average air temperature and DLI data are means of average values logged 15 min.

Production period ^a	Avg temp [mean $\pm$ SD ($^{\circ}$ C)] ^y		Avg DLI [mean $\pm$ SD ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)]	
	Field	High tunnel	Field	High tunnel
1 to 31 July	23.1 $\pm$ 3.3	23.8 $\pm$ 2.9	53.3 $\pm$ 8.7	43.1 $\pm$ 6.6
1 to 31 Aug.	22.3 $\pm$ 4.9	22.7 $\pm$ 4.9	52.0 $\pm$ 11.1	31.8 $\pm$ 9.8
1 to 30 Sept.	19.5 $\pm$ 7.8	19.9 $\pm$ 7.0	42.0 $\pm$ 11.2	24.1 $\pm$ 7.3
1 to 18 Oct.	15.3 $\pm$ 8.7	15.9 $\pm$ 8.1	27.8 $\pm$ 9.6	19.1 $\pm$ 7.0

^aMeasured from transplant until the end of the last harvest.

^y(1.8 $\times$ $^{\circ}$ C) + 32 = $^{\circ}$ F.

and greatest width of an individual reflexed flower. Celosia flower length and width was determined by measuring the distance from base to the top of the cockscomb and the greatest width of the cockscomb, respectively.

The experiment was laid out in a randomized complete block design. For each crop, four blocks were grown in the field and four blocks were grown in the high tunnel. The experiment was not repeated in time due to damage and loss of the high tunnel structure and as a result, no further investigations were conducted. Data were analyzed using SAS (version 9.2; SAS Institute, Cary, NC) mixed model procedure (PROC MIXED) and mean separations between treatments were performed using Duncan's least significant difference test at $P \leq 0.05$. For dianthus, matricaria, and snapdragon, data on the total number of stems harvested per week were pooled between the field and high tunnel because no significant difference occurred between the interaction of environment and harvest week.

Results

BELLFLOWER. The total number of stems harvested each week from both the field and high tunnel increased from weeks 34 to 38 (5-week period) and then decreased (Table 2). However, there were no significant differences in number of stems harvested each week from the field and high tunnel. Stem caliper was 18% greater for flowers harvested in the field (Table 3).

BELLS OF IRELAND. During the first 3 weeks of harvest, a total of ≈ 29 more stems were harvested from the high tunnel than from the field (Table 2). Field and high tunnel production yielded 8 and 17 stems/ m^2 , respectively (Table 3). Stems harvested in the high tunnel were on average 9.5 cm (15%) longer than those in the field.

Compared with field production, high tunnel production yielded 120% more stems per square meter, had 13% longer and 22% larger flowers (calyx) by width, and TTH was reduced by 6 d.

CELOSIA. In week 33, a total of about five more stems were harvested from the high tunnel than from the field (Table 2). The total number of stems harvested each week from the field increased, compared with the high tunnel. Compared with field production, high tunnel production yielded stems that were on average 16.8 cm (16%) longer, had a 11% larger stem caliper, and flowers (cockscomb) that were 12% longer and 14% larger by width (Table 3). High tunnel production TTH was reduced by 3 d over field production. However, field-grown stems had 1.5 more cockscombs compared with stems grown in the high tunnel.

DIANTHUS. The total number of stems harvested each week increased for 5 weeks and then decreased (Table 2). Compared with high tunnel production, stems harvested from the field were on average 8.9 cm (18%) longer and had a 16% larger stem caliper (Table 3). However, stems harvested from the high tunnel had 5% larger (length and width) flowers and TTH was reduced by 7 d over field production.

GOMPHRENA. The total number of stems harvested each week from both the field and high tunnel were similar for weeks 33 and 34 and the weekly yield increased as time from first harvest increased (Table 2). Stems harvested from the high tunnel were on average 6.7 cm (44%) longer compared with those harvested from the field (Table 3).

MATRICARIA. The total number of stems harvested each week increased from weeks 35 to 38 and then decreased (Table 2). Compared with field

production, high tunnel production yielded stems that were 6.7 cm (19%) longer (Table 3).

SNAPDRAGON. The total number of stems harvested each week decreased as the time from first harvest increased (Table 2). The number of marketable cut flower stems harvested per square meter, stem length, stem caliper, flower number, flower length, flower width, and TTH was not influenced by production environment (Table 3).

Discussion

High tunnels provide a number of environmental, cultural, and economical advantages for spring, summer, and fall cut flower production (Ortiz et al., 2012; Wien, 2009; Wien and Pritts, 2009). Compared with field-grown crops, high tunnels generally improve yield, quality, and marketability of cut flowers. For instance, when crop productivity is compared on a per unit time basis, high tunnel cut flowers produce more stems per week than those grown in the field (Wien, 2009). Similarly, in our study, the total number of celosia and bells of ireland stems harvested from the high tunnel was significantly greater at weeks 33 and 37 to 39, respectively, compared with those harvested from the field. Similarly, Ortiz et al. (2012) reported that high tunnel-grown 'Amazon Neon Cherry' dianthus and 'Benary Giant Scarlet' zinnia (*Zinnia elegans*) produced a higher number of harvestable stems earlier, compared with those harvested from the field.

However, production environment did not significantly influence the total number of stems harvested per week for all species. For example, the number of dianthus, matricaria, and snapdragon stems harvested decreased as the number of harvest weeks

increased. A similar trend for ‘Potomac Orange’ snapdragon and ‘Katz Lavender Blue’ stock (*Matthiola incana*) was observed by Ortiz et al. (2012). The snapdragon cultivars representing the Potomac series reported here and by Ortiz et al. (2012) performed similarly as both were planted in the late to very late seasons, whereas the dianthus cultivars of the Amazon Neon series differed. We attribute this to the differences in planting seasons between the two studies and not cultivar variation within a series.

In contrast to early-season planting (Ortiz et al., 2012), the number of marketable stems harvested per square meter from both the field and high tunnel were similar for all species, with the exception of bells of ireland. High tunnel-grown bells of ireland yielded nine stems/m² more compared with field production. Ortiz et al. (2012) reported the number of marketable stems per square meter harvested from the high tunnel in early-season planting significantly increased for ‘Rocket Red’ snapdragon, ‘Red Chief’ celosia, ‘Amazon Neon Cherry’ dianthus, and ‘Benary Giant Scarlet’ zinnia compared with the field. However, they found no significant difference in the number of stems per square meter harvested from both field and high tunnel production for ‘Potomac Orange’ snapdragon (very-late season planting) and stock (early-season planting). In our study, ‘Potomac Lavender’ snapdragon performed similar to the ‘Potomac Orange’ snapdragon reported by Ortiz et al. (2012). Alternatively, ‘Bombay Firosa’ celosia and ‘Amazon Neon Purple’ dianthus in our study yielded similar numbers of marketable stems per square meter in both environments compared with ‘Red Chief’ celosia and ‘Amazon Neon Cherry’ dianthus reported by Ortiz et al. (2012).

When selecting cultivars for specialty cut flower production, traits of importance include stem length, stem strength, earliness to flower, pest and disease resistance, heat tolerance, and vase life (Kelly, 1991; Ortiz et al., 2012). Previous research has demonstrated similar or improved cut flower quality when crops were grown in high tunnels compared with field production (Ortiz et al., 2012; Wien, 2009). In this study, cut flower stems harvested from the high tunnel were significantly longer than stems

Table 2. The effect of growing environment (E; field or high tunnel) and harvest week (W) on the total number of bellflower, bells of ireland, celosia, dianthus, gomphrena, matricaria, and snapdragon cut stems harvested each week from the field or high tunnel at Meigs Farm (Tippecanoe, IN).

Harvest week no.	Cut stems (no.)	
	Field	High tunnel
Bellflower		
34	0.9 bA ^z	1.9 bA
35	3.9 bA	5.1 abA
36	4.0 bA	3.5 abA
37	8.6 aA	4.9 abA
38	11.6 aA	7.0 aA
39	2.5 bA	3.4 abA
40	0.5 bA	1.9 bA
E		NS ^y
W		***
E × W		*
Bells of ireland		
37	1.5 bB	6.0 cA
38	4.3 bB	20.6 abA
39	6.0 bB	13.8 bcA
40	19.1 aA	27.3 aA
E		***
W		***
E × W		NS
Celosia		
33	1.8 bB	6.4 aA
34	13.3 aA	13.3 aA
35	20.0 aA	6.3 bA
E		NS
W		**
E × W		*
Dianthus		
35		0.8 c ^x
36		1.8 c
37		23.8 b
38		66.9 a
39		11.5 bc
40		7.6 bc
E		NS
W		***
E × W		NS
Gomphrena		
33	27.0 cA	20.3 cA
34	36.6 cA	35.5 cA
35	97.4 bA	75.6 bB
36	158.3 aA	132.9 aB
E		*
W		***
E × W		NS
Matricaria		
35	4.1 cd	
36	10.7 bc	
37	11.8 b	
38	29.9 a	
39	3.8 cd	
40	2.4 d	
E		NS
W		***
E × W		NS

(Continued on next page)

Table 2. (Continued) The effect of growing environment (E; field or high tunnel) and harvest week (W) on the total number of bellflower, bells of ireland, celosia, dianthus, gomphrena, matricaria, and snapdragon cut stems harvested each week from the field or high tunnel at Meigs Farm (Tippecanoe, IN).

Harvest week no.	Cut stems (no.)	
	Field	High tunnel
Snapdragon		
32	17.7 a ^w	
33	6.8 b	
34	2.3 c	
35	1.6 c	
36	1.3 c	
E	NS	
W	***	
E × W	NS	

^wWithin-column means followed by different lower-case letters are significantly different by Duncan's least significant difference (LSD) test at $P \leq 0.05$. Within-row means followed by different upper-case letters are significantly different by Duncan's LSD test at $P \leq 0.05$.

^vData were pooled across environment.

^xTwo-way analysis of variance for the main effects and interactions of E and W.

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

harvested from the field for bells of ireland, celosia, gomphrena, and matricaria. High tunnel production yielded a larger stem caliper for celosia, whereas field production yielded larger stem caliper for bellflower and dianthus. High tunnel production did not significantly influence the number of flowers; however, field production yielded significantly more celosia cockscombs per stem. High tunnel production yielded stems with overall larger flowers compared with the field for bells of ireland, celosia, and dianthus. Our results are in agreement with previous reports which indicate that cut flower stems harvested from a high tunnel environment are of higher quality (Ortiz et al., 2012; Wien, 2009).

Stem length, stem strength, and the number of flowers on the stem are very important when determining cut flower stem quality and marketability. For instance, most florists prefer longer stem lengths than mass market outlets (Starman et al., 1995). Longer stems may be desirable for a florist, but a long stem with a small stem caliper has greater incidence of bending or breaking (Ortiz et al., 2012), thus compromising stem quality. To satisfy the potential market, cut flower growers can consider the minimum marketable stem length to be between 30 and 41 cm (Ortiz et al., 2012; Starman et al., 1995). Similar to Ortiz et al. (2012), we used 30 cm as the minimum length for a stem to be considered marketable. Our results indicate that cut flower stems harvested in the high tunnel were longer and thicker for

all species, with the exception of bellflower, dianthus, and snapdragon. As mentioned previously, the dianthus cultivar in this study is similar to the one reported by Ortiz et al. (2012), which determined stem length and stem caliper for 'Amazon Neon Cherry' dianthus to be similar regardless of production environment.

During the months of July, August, September, and October the DLI in the field was (mean $\pm$ SD) 53.3 ± 8.7 , 52.0 ± 11.1 , 42.0 ± 11.2 , and 27.8 ± 9.6 mol·m⁻²·d⁻¹, respectively. Likewise, the DLI in the high tunnel was 43.1 ± 6.6 , 31.8 ± 9.8 , 24.1 ± 7.3 , and 19.1 ± 7.0 mol·m⁻²·d⁻¹, respectively. Light transmission in the high tunnel was reduced by $\approx 19\%$, 39% , 43% , and 44% , which may be attributed to the age (3 years), shading of the high tunnel frame, polyethylene glazing material, shading from the cut flower crops, and seasonal angle of the sun. Similarly, Ortiz et al. (2012) reported a reduction of light transmission by only $\approx 23\%$ (new glazing). Although crops in the high tunnel received a lower DLI, stem length was longer or comparable to crops grown in the field. Previous reports have also indicated cut flowers developed significantly longer stems in high tunnels as a result of reduced air movement and irradiance (Ortiz et al., 2012; Wien, 2009; Wien and Pritts, 2009). Furthermore, cut flowers grown in the high tunnel protected from winds may exhibit seismomorphogenic responses described by Mitchell et al. (1975).

Time to harvest is another consideration for specialty cut flower growers, especially for early-season production. Reduced TTH was observed for celosia, dianthus, and bells of ireland when grown in the high tunnel compared with the field. Similarly, Ortiz et al. (2012) demonstrated reduced TTH for early-season plantings of celosia, dahlia (*Dahlia ×hybrida* 'Karma Thalia Dark Fuchsia'), dianthus, and very-late season planting of sunflower (*Helianthus annuus* 'Premier Lemon') when crops were high tunnel grown, rather than field grown. Earlier harvests will allow for earlier marketability and return on investment, and the ability to keep the growing area filled while reducing input and labor costs. Furthermore, the small reduction in TTH may be the result of our late-season planting, and thus similar growing temperatures in both the high tunnel and field (Table 1).

The quantitative and qualitative parameters measured in this study would have varying levels of economic return. An increased number of stems and reduced TTH would have a high economic return and justify the cost of growing in a high tunnel. According to our results, late-season high tunnel planting and production of bells of ireland would have a high economic return considering the increased number of stems harvested, higher stem and flower quality parameters, and reduced TTH. Longer and thicker cut flower stems and more and larger flowers would have a moderate-to-low economic return depending on the market. Late-season high tunnel planting and production of celosia, matricaria, and gomphrena resulted in increased stem length and increased stem caliper of celosia. Celosia and dianthus stems harvested in the high tunnel had more flowers that were larger or flowers were larger, respectively. Although, the economic impact of producing bellflower and snapdragon in a high tunnel was not observed in the present study, growers should consider the cultural benefits that high tunnels provide compared with field production.

The results of this study suggest that late-season planting in a high tunnel offers some benefits over field production of the specialty cut flowers trialed. Overall, stem and flower quality

Table 3. The effect of field or high tunnel environment (E) on the number of marketable cut flower stems harvested per square meter, stem length, stem caliper, flower number, flower length, flower width, and time to harvest (TTH) of bellflower, bells of ireland, celosia, dianthus, gomphrena, matricaria, and snapdragon grown in a field or high tunnel at Meigs Farm (Tippecanoe, IN) in 2013.

Environment	Stems (no./m ²) ^z	Stem length (cm) ^z	Stem caliper (mm) ^z	Flower (no.)	Flower length (cm)	Flower width (cm)	TTH (d)
Bellflower							
Field	3.8 a ^y	34.3 a	7.1 a	9.7 a	4.7 a	4.7 a	40.0 a
High tunnel	3.2 a	34.2 a	6.0 b	8.1 a	4.5 a	4.6 a	39.9 a
E ^x	NS	NS	**	NS	NS	NS	NS
Bells of ireland							
Field	7.6 b	60.5 b	8.0 a	29.3 a	2.3 b	2.3 b	63.2 a
High tunnel	16.7 a	70.0 a	8.2 a	29.8 a	2.6 a	2.8 a	56.8 b
E	***	***	NS	NS	**	***	***
Celosia							
Field	10.0 a	104.1 b	16.8 b	4.0 a	9.8 b	8.5 b	52.8 a
High tunnel	7.4 a	120.9 a	18.8 a	2.5 b	11.0 a	9.7 a	49.6 b
E	NS	***	*	*	*	**	***
Dianthus							
Field	16.8 a	58.2 a	6.4 a	19.6 a	2.0 b	2.0 b	66.0 a
High tunnel	18.5 a	49.3 b	5.5 b	17.4 a	2.1 a	2.1 a	58.7 b
E	NS	***	*	NS	*	*	***
Gomphrena							
Field	35.7 a	37.0 b	2.9 a	1.5 a	2.7 a	2.5 a	45.6 a
High tunnel	35.7 a	43.7 a	3.5 a	1.4 a	2.6 a	2.5 a	45.6 a
E	NS	**	NS	NS	NS	NS	NS
Matricaria							
Field	8.5 a	32.4 b	4.5 a	8.8 a	1.4 a	1.3 a	49.0 a
High tunnel	8.1 a	38.7 a	4.8 a	8.0 a	1.5 a	1.4 a	48.1 a
E	NS	***	NS	NS	NS	NS	NS
Snapdragon							
Field	4.4 a	61.5 a	6.9 a	18.3 a	4.1 a	4.3 a	38.6 a
High tunnel	6.9 a	65.5 a	6.7 a	18.9 a	4.2 a	4.4 a	38.6 a
E	NS	NS	NS	NS	NS	NS	NS

^z1 stem/m² = 0.0929/ft², 1 cm = 0.3937 inch, 1 mm = 0.0394 inch.

^yWithin-column means followed by different lower-case letters are significantly different by Duncan's least significant difference (LSD) test at $P \leq 0.05$.

^xAnalysis of variance for the effect of E: NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

obtained here are cultivar specific and performance may vary with other cultivars. Our results indicate that summer and fall high tunnel production is suitable for bells of ireland, 'Bombay Firosa' celosia, 'Amazon Neon Purple' dianthus, 'Fireworks' gomphrena, and 'Vegmo Snowball Extra' matricaria. Therefore, growers in the midwestern U.S. plant hardiness zone 5b will be able to use this information to introduce diversity to their specialty cut flower production program and market.

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