Improving Snapdragon Cut Flower Production through High Tunnel Season Extension, Transplant Timing, and Cultivar Selection

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Abstract. The demand for locally grown, specialty cut flowers is increasing and now includes nontraditional regions for production, such as the U.S. Intermountain West. The objective of this study was to evaluate snapdragon (*Antirrhinum majus* L.) as a cool season, cut flower crop in northern Utah, where the high elevation and semiarid climate result in a short growing season with strong daily temperature fluctuations. High tunnel and field production methods were trialed in North Logan, UT (41.77°N, 111.81°W, 1382 m elevation) with cultivars ‘Chantilly’, ‘Potomac’, and ‘Rocket’ in 2018 and 2019. Each year, five to six transplant timings at 3-week intervals were tested, beginning in early February in high tunnels and ending in late May in an unprotected field. Stems were harvested and graded according to quality and stem length. High tunnels advanced production by 5 to 8 weeks, whereas field harvests continued beyond the high tunnel harvests by 2 to 8 weeks. High tunnels yielded 103 to 110 total stems per m² (65% to 89% marketability), whereas field yields were 111 to 162 total stems per m² (34% to 58% marketability). Overall, production was the greatest with March transplant timings in the high tunnels and mid-April transplant timings in the field. ‘Chantilly’ consistently bloomed the earliest on 4 and 6 May each year, ‘Potomac’ had the highest percentage of long stem lengths, and ‘Rocket’ extended marketable stem production through July in high tunnels. Selecting optimal transplant dates in the high tunnel and field based on cultivar bloom timing maximizes marketable yields and results in a harvest window lasting 4.5 months.

Across the United States, growers have developed local, niche markets for specialty cut flower crops that are in demand by U.S. consumers for their unique blooms and fresh

quality (Armitage and Laushman, 2003). Stems are typically sold wholesale to local retail businesses, such as florists, or as prearranged bouquets in direct markets, such as farmers markets, farm stands, and community-supported agriculture subscriptions (Connolly and McCracken, 2016). These markets, combined with increasing public demand for local agricultural products (Wolfe and McKissick, 2007; Yue et al., 2011; Zongyu et al., 2016), have led to an increase in cut flower farms across the U.S. national membership in the Association of Specialty Cut Flower Growers (ASCFG) reflects this: there are now 1980 members (Judy Laushman, personal communication, 21 Aug. 2020), a quadrupling in membership since 2008. Included in this growth are nontraditional regions for cut flower production, such as the U.S. Intermountain West, where 86 small-scale farms have been established in Utah and southern Idaho, as well as a Utah-based cut flower farmer association that gained 114 members since launching in mid-2019 (Utah Cut Flower Farm Association, 2021).

Local trials are critical for optimizing cut flower production against regional constraints (Ortiz et al., 2012; Wien, 2009). Surveys of growers emphasize this need with season

extension, control of bloom timing, and cultivar selection as the top-ranked regional research priorities in a survey conducted at the 2019 Utah Urban and Small Farms Conference (Cut Flower Growers Survey, 20 Feb. 2019), and season extension and control of bloom timing were top needs across the United States and Canada (Loyola et al., 2019). Growing in a low-cost high tunnel can advance and increase production by stabilizing environmental conditions (Lamont, 2009; Wells and Loy, 1993), particularly for cool-season crops. Passive heating advances planting and harvest to meet early market demands (Starman et al., 1995; Wien, 2009). High tunnels also offer physical protection from late snowstorms and rainfall that can damage the crop (Lamont, 2009; Wien, 2009). Later in the growing season, high tunnels can be transformed into shade structures by replacing the plastic film covering with shadecloth to reduce temperature and solar radiation (Wien, 2009). For cut flower production, shade may have additional benefits, such as increasing stem length, and hence marketable yields (Armitage, 1991).

Snapdragons (*Antirrhinum majus*) are a cool-season crop that florists have indicated interest in regularly sourcing from local growers (Wolfe and McKissick, 2007). Although pricing varies by stem length grade and daily demand throughout the year, typical wholesale prices per 10-stem bunch ranged from \$8.50 to \$10.00 for short and medium stem lengths and \$12.00 to \$15.00 for long and extralong lengths (USDA Agricultural Marketing Service, 2019). Local wholesalers have indicated that there is a preference for stems of 92-cm length, which are shipped upright to prevent stem curvature (Roger Callister, personal communication, 22 Mar. 2021). Therefore, farm revenues may be increased with production practices that can consistently supply longer stems, stored upright, over a greater window of time.

Key factors influencing snapdragon stem length and bloom timing are daylength and temperature. As quantitative long day plants (Armitage and Laushman, 2003; Owen et al., 2018), snapdragons will flower under short days, but days to flowering decreases as the daylength and light intensity increases (Adams et al., 2003; Cremer et al., 1998; Warner and Erwin, 2005). However, as light duration and intensity increase, stem length decreases (Gutierrez, 2003). The optimal temperature range for snapdragons is 7 to 18 °C and varies by cultivar (Armitage and Laushman, 2003), which are grouped I through IV, according to flower initiation response to temperature, daylength, and light intensity (Dole and Wilkins, 1999; Larson, 1992). Group I–II cultivars, such as ‘Chantilly’, bloom the earliest under shorter days and require minimum temperatures of 7 to 13 °C (Armitage and Laushman, 2003; Dole and Wilkins, 1999) with 6.2 to 18.6 MJ·m⁻²·d⁻¹ (Ball Horticulture, 2011), whereas ‘Potomac’ (Group III–IV) and ‘Rocket’ (Group IV) bloom the latest and require nighttime temperatures of 13 to 16 °C, longer daylength, (Armitage and Laushman,

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2003; Dole and Wilkins, 1999) with 15 to 31 MJ·m⁻²·d⁻¹ (Ball Horticulture, 2021). Across cultivars, the maximum temperature is 31 °C (Runkle, 2010), indicating an adaptability to lower temperature and light conditions as a cool-season crop.

On the basis of these growth requirements, snapdragons have strong production potential in the U.S. Intermountain West, and trials in the U.S. Midwest and Southeast help establish baseline transplant dates, harvest timing, and yield. In a field trial in Tennessee (USDA-ARS, 2012; USDA Hardiness Zone 7a), ‘Rocket Bronze’, ‘Rocket Pink’, and ‘Rocket White’ (Group IV) were transplanted 5 May and began blooming in early June (Starman et al., 1995). The total yield averaged 16 to 30 stems per plant (112 to 210 stems/m²) and 36 to 45 cm stem lengths which (Starman et al., 1995). Some researchers have used a grading standard of 30 to 41 cm for marketable stems (Kluza, J. 2019; Ortiz, et al., 2012; Owen, et al., 2016; Starman, et al., 1995), whereas others have used 46 cm as the grading minimum for marketable stems according to the Society of American Florists (Carter and Grieve, 2008; Dole and Wilkins, 1999; Miller, 1961). In Indiana [USDA Hardiness Zone 5b; USDA Agricultural Research Service (ARS), 2012], ‘Rocket Red’ (Group IV) was planted on 16 and 17 May, 1 week after the last frost date; this yielded an average of 183 stems per m² and 51.8 cm stem lengths in the high tunnel, and 158 stems per m² and 39 cm in the field, indicating that high tunnels can significantly increase both production quantity and quality (Ortiz et al., 2012). In North Dakota (USDA Hardiness Zones 3b to 4a, USDA-ARS, 2012), a mix of ‘Rocket’ varieties and ‘Potomac White’ were planted 20 May through 10 June 2016 and 24 April through 2 June 2017 (Kluza, 2019), up to 7 weeks before the last frost date (North Dakota State University, 2016). These early plantings yielded an average of 241 stems per m² with 43 cm stem lengths in the high tunnel and 120 stems per m² with 30 cm stem lengths in the field (Kluza, 2019). Although high tunnel use (Kluza, 2019; Ortiz et al., 2012; Starman et al., 1995), cultivar selection (Kluza, 2019; Ortiz et al., 2012; Starman et al., 1995; Wien, 2013), and multiple transplanting dates (Kluza, 2019) have been explored independently, testing combinations of I–II and III–IV groups with staggered transplant dates under high tunnel and field production systems have not been evaluated and may further increase production and extend the harvest season.

To promote stem elongation during late spring and provide summer production, shade-cloth may be used to reduce light intensity, but this may increase time to flowering (Armitage, 1991; Li et al., 2017; Wien, 2009). Compared with an unshaded control, snapdragon stem lengths were 2 cm longer under 30% shade and 17 cm longer under 60% shade (Alhajhoj and Munir, 2016). However, compared with the unshaded control, 30% shade delayed flowering by 7 d and 60% shade delayed flowering by 39 d (Alhajhoj and Munir, 2016). These trials were conducted in Al-Ahsa, Saudi Arabia,

where average solar radiation ranges 19.6 to 25.3 MJ·m⁻²·d⁻¹ during March through July (Alhajhoj and Munir, 2016), compared with 13.7 to 29.1 MJ·m⁻²·d⁻¹ in northern Utah (Logan, UT) (Utah Climate Center, 2020a). In Starkville, MS, where average solar radiation ranges 14.9 to 21.3 MJ·m⁻²·d⁻¹ in March through July (Delta Agricultural Weather Center, 2021), the stem length of ‘Potomac Red’ significantly increased from 86.2 cm in full sun to 98.9 cm under 50% shade for the first spring harvest (Li et al., 2017). However, shade delayed springtime harvests by 1 week, stem length was not significantly different from unshaded controls in subsequent harvests, nor was there a significant difference in total yield per plant (Li et al., 2017), indicating a trade-off for using shade to maximize stem length of initial yields.

The use of high tunnels with field production, multiple snapdragon cultivar groups at staggered transplant timings, and shading could result in greater yields with improved stem quality for an extended growing season. Therefore, the objectives of this study were to 1) evaluate high tunnel and field production practices on snapdragon bloom timing, yield, and quality; 2) trial snapdragon cultivars across groups, including ‘Chantilly’ (I), ‘Potomac’ (III–IV), and ‘Rocket’ (IV), for both their productivity in the U.S. Intermountain Mountain West and ability to stagger production; and 3) determine optimal transplant timings to lengthen the harvest season and produce a high-quality crop.

Materials and Methods

Site Description. Trials were conducted at the Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT (lat. 41.77°N, long. 111.81°W, 1382 m elevation, 135 freeze-free days, an average last frost date on 15 May, and USDA Hardiness Zone 5) during 2018–19 (Utah Climate Center, 2020b; USDA-ARS, 2012). The soil is a Millville silt loam with 2% organic matter. Production was evaluated in high tunnel and unprotected field conditions. Two quonset-style high tunnels, each 4.3 m wide × 11.8 m long, were oriented east to west (Black et al., 2008). Each high tunnel contained two, 1.1 m wide × 11.8 m long beds. The adjacent, unprotected field was 4.3 m wide × 11.6 m long in 2018, 6.7 m wide × 9.7 m long in 2019, and contained three beds that were 1.1 m wide × 9.7 m long each year.

Plots (0.83 m²) within each bed were established to independently evaluate the high tunnel and field production of three cultivars, Chantilly, Potomac, and Rocket, at selected transplanting times. In the high tunnel (HT), the transplant timings were early February (HT-EF), early March (HT-EM), late March (HT-LM), and early April (HT-EA). The field (F) was transplanted in late April (F-LA) and late May (F-LM). Corresponding reference transplant timing and actual dates in 2018 and 2019 were as follows: HT-EF (9 Feb. 2018), HT-EM (2 Mar. 2018, 7 Mar. 2019), HT-LM (23 Mar. 2018 and 26 Mar. 2019), HT-EA (13

Apr. 2018, 12 Apr. 2019), F-LA (26 Apr. 2018, 24 Apr. 2019), and F-LM (22 May 2018, 27 May 2019). In 2018, only ‘Chantilly’ and ‘Potomac’ were planted during HT-EF, and this transplant timing was not repeated in 2019.

Site preparation. High tunnels were covered with a single layer of 0.15-mm greenhouse film (Tufflite, IV Clear, Grand Rapids, MI) in the fall before significant snowfall. Soils were rototilled each spring and a slow-release fertilizer (Nutricote Total Type 100, 18N–6P–8K, New York, NY) was incorporated at a rate (g·m⁻²) of 20.9 N, 1.3 P, and 6.4 K. Three lines of drip tape (Toro, Aqua-Traxx, 1.29 lph per emitter at 68947.6 Pa, 10 cm in-line emitter spacing, Bloomington, MN) were spaced 45 cm apart on tilled beds and covered with 0.025-mm black plastic mulch (Robert Marvel, embossed plastic, Annville, PA), which has shown to double snapdragon stem yields compared with bare ground (Sherrer et al., 2013). Plants were spaced on a 0.23-m grid, for a total of 16 plants per plot in 2018 and 18 plants per plot in 2019.

Plant culture. Seeds were sown in 128-plug trays using soilless media (Sungro, Sunshine Mix #4, Agawam, MA), covered with a thin layer of vermiculite (Therm-O-Rock, Vermiculite, Pittsburgh, PA, U.S.), and grown in a greenhouse until transplanting. Fertilizer (Peters Excel, 21–5–20, Allentown, PA) was applied twice per week at a concentration of 100 ppm N. From germination until transplant, plugs were provided supplementary light for at least 6 h every day for a total photoperiod of 16 h. Temperature was maintained at 21 °C during the day and 15 °C at night. Plugs were treated for white flies using insecticide (Marathon II, Bluffton, SC) as needed. Five weeks later, once plants had four to six sets of true leaves, stems were pinched, leaving three nodes to encourage multistemmed plants. One week after pinching, plugs were directly transplanted into the high tunnel or field plots and were not hardened off.

High tunnel and field management. After transplant, floating rowcovers (Agribon, AG-19, 19 g/m², 85% light transmission, San Luis Potosi, Mexico) were used in the high tunnel through mid-April to reduce damage from overnight, freezing temperatures, as the air temperature within a high tunnel is only elevated by 3 to 5 °C compared with outdoor ambient temperatures at night (Wien et al., 2006). The addition of low tunnels can increase the temperature around plants by 3 to 5 °C (Wien et al., 2006) allowing protection within the high tunnel when ambient temperatures fall below –4 to –10 °C. After removal of the covers in the high tunnels, a horizontal trellis system of nylon mesh (Tenax Hortonova, 15 cm² trellis netting, Vigano, Italy) was installed in both the high tunnel and the field to encourage straight, marketable stems (Larson, 1992). Soil moisture was monitored at a 0.2, 0.46, and 0.61 m depth using a Watermark sensor (Irrometer Company, Riverside, CA) placed in each row and irrigated at a –60 kPa soil water potential. Irrigation events typically occurred every 2

weeks in the spring and fall and at least once per week in summer.

High tunnel temperature was managed by manually venting the structure based on field weather conditions reported from an automated weather station located 0.2 km from the tunnels at the Greenville Station (Utah Climate Center, 2020b). A temperature range of 10 to 21 °C was maintained by opening the window vents located on the end walls when solar radiation was greater than 400 W·m⁻² and outside air temperature was greater than 5 °C; the doors were opened when air temperature was 15 °C, and the sides of the high tunnel were raised when air temperature was 25 °C. Each year in late May, the high tunnel film was removed and replaced with 30% shade fabric (DeWitt, Woven Shadecloth Fabric, Sikeston, MO). In May 2019, two of the four field replications were also covered in 30% shade that was installed on the south side of low tunnel arches (Maughan et al., 2018) to compare with production under full sun. Starting in late June, plants were fertigated at a rate of (g·m⁻²): 2 N, 0.87 P, and 1.66 K (Peters, 20–20–20, Allentown, PA) every 3 weeks to promote new growth. Horizontal nylon mesh trellis was moved upwards with crop growth to reduce incidence of stem curvature. In 2019, yield declined in late July within the high tunnel, and stems were trimmed back to three to four nodes to promote and evaluate new growth in cooler late-summer to fall conditions.

Data collection and analysis. Stems were harvested, leaving one to four nodes at the base of each stem three times per week (e.g., Monday, Wednesday, Friday), when one-third of the florets were open. After harvest, each stem was graded as a marketable or cull based on length and visual quality by adapting standards from the Society of American Florists (Miller, 1961; Dole and Wilkins, 1999). Marketable stems were ≥46 cm and straight (no curvature), with a properly developed raceme and no visual damage. Marketable stems were further graded according to minimum stem length categories of “first” (46–60 cm stem length), “extra” (61–75 cm), “fancy” (76–90 cm), and “special” (>91 cm). Stems were culled if the length class was “utility” (shorter than 46 cm), or if they exhibited curvature, malformed blooms, or other visual damage from insects or disease.

All marketable stems were sold through local markets, May through September, in bunches of five stems. Total yield, calculated by stems per m², is represented by T²⁰, T⁵⁰, and T⁸⁰ when harvested yield reaches 20%, 50%, and 80% of total yield.

Statistical analysis. A randomized complete block design was used in the high tunnel trials, with blocking by tunnel and beds. Cultivars and transplant timing combinations were randomly assigned to plots within each block. There were four replications per cultivar × transplant date treatment in 2018 and three replications in 2019. In the field, a completely randomized design was used; thus, the high tunnel and field trials were analyzed independently. There were four replications per treatment in the field across both years. A mixed model for high tunnel data and a two-way analysis of variance for field data were used to analyze the total yield and marketable yield with PROC GLIMMIX of SAS/STAT 15.1 (SAS Institute; Cary, NC). Cultivar, transplant timing, and their interaction were fixed effects in both models. Within the mixed model for high tunnels, tunnel and beds were random factors. Interactions between cultivar and transplant timings were highly nonsignificant in the models, and therefore main effects of cultivar and transplant timings were estimated. Pairwise comparisons among cultivars and among transplant timings were evaluated with Tukey-Kramer’s method to adjust for multiplicity. Significance level was defined at the 0.05 level. Note that after-preliminary data indicated that HT-EF underperformed in 2018, the transplant period was not repeated in 2019, and statistical analyses were not performed for HT-EF nor 2018 yields of ‘Rocket’ due to a lack of replication.

Results

Environmental conditions. Weather data are given in Table 1. Overall, the average and minimum field air temperatures were warmer and fluctuated less in 2018 than in 2019, particularly from February through July. The total precipitation was greater in 2019 than in 2018. Although less total precipitation fell in May 2019 than in May 2018, the majority fell from 16 to 28 May, which delayed the F-LM planting in 2019 by 5 d. The average daily solar radiation was similar across years

and ranged from a low of 9 MJ·m⁻²·d⁻¹ in February to up to 30 MJ·m⁻²·d⁻¹ in June. In the high tunnel, the average air temperature was 7.3 °C higher than in the field by March and 10 °C cooler by July of each year.

Production in high tunnel and field. High tunnel harvests began 4 and 6 May and ended on 30 and 31 July each year (Fig. 1). The total yield ranged from 79 (± 6 SE) to 119 (± 8 SE) stems per m², whereas marketable yields ranged 53 (± 4 SE) to 97 (± 7 SE) stems per m² (Table 2). In the field, harvests began 13 June and 1 July and ended on 10 Aug. and 26 Sept. each year (Fig. 1). The total yield ranged from 85 (± 5 SE) to 197 (± 18 SE) stems per m² across years, while marketable yields ranged 35 (± 5 SE) to 80 (± 5 SE) stems per m² (Table 3).

Production by transplant timing. Each year, HT-EM and HT-LM transplant timings resulted in the greatest total (92–121 stems/m²) and marketable (63–95 stems/m²) yields; yields for these timings were not significantly different in either year (Table 2). On the other hand, HT-EA averaged 64 (± 6 SE) to 79 (± 5 SE) total and 36 (± 8 SE) to 62 (± 5 SE) marketable stems per m² each year, which were significantly lower than yields from HT-EM and HT-LM timings (Table 2). Across all cultivars in high tunnel production, HT-EM reached harvest yields T²⁰, T⁵⁰, and T⁸⁰ up to 10 d earlier than HT-LM and up to 17 d earlier than HT-EA (Fig. 1). For the field, F-LA transplants produced an average of 98 to 209 total and 53 to 59 marketable stems per m² each year, whereas F-LM averaged 91 to 100 total and 36 to 56 marketable stems per m² (Table 3). Although transplanting in F-LA resulted in greater total and marketable yields than F-LM in both years, differences were only significant in 2019 (Table 3). Across all cultivars in field production, F-LA reached harvest yields T²⁰, T⁵⁰, and T⁸⁰ 5 to 20 d earlier than F-LM (Fig. 1).

Production by cultivar × transplant timing. T²⁰, T⁵⁰, and T⁸⁰ were 4 to 7 d earlier for ‘Chantilly’ × HT-EF than ‘Chantilly’ × HT-EM, whereas ‘Potomac’ × HT-EF was 1 d earlier to 4 d later than ‘Potomac’ × HT-EM (Fig. 1). Total and marketable yields for the HT-EF or HT-EM transplant timings were not significantly different for either cultivar (Fig. 1), thus the HT-EF timing was not repeated in 2019. The average total and

Table 1. Air temperature in the high tunnel and field in North Logan, UT, as monthly averages (Avg), minimums (Min), and maximums (Max); average daily solar radiation; and total monthly precipitation for 2018 and 2019 growing seasons. Plastic was removed from high tunnels and replaced with 30% shadecloth on 29 May in 2018 and May 30 in 2019.

Year	High tunnel air temperature (°C)						Field air temperature (°C)						Solar radiation (MJ·m ⁻² ·d ⁻¹)		Precipitation (mm)	
	2018			2019			2018			2019			2018	2019	2018	2019
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max				
February	3.1	−4.4	23.4	— ^z	— ^z	— ^z	0.4	−4.1	2.6	−2.1	−6.4	1.8	8.6	9.4	1.1	3.5
March	10.6	−1.4	33.1	10.6	−1.1	30.9	3.3	−1.4	6.0	2.5	−2.4	7.9	13.4	14.4	4.2	6.2
April	12.9	3.5	29.6	13.0	3.4	31.3	9.5	3.1	12.7	8.8	−0.7	14.4	18.4	16.2	7.8	5.0
May	15.5	7.6	29.9	14.3	5.2	31.4	14.8	8.0	18.5	12.4	5.8	19.0	23.7	23.6	6.0	5.0
June	18.7	9.9	30.1	18.0	7.8	28.9	19.0	11.0	22.9	17.5	9.5	24.6	29.5	26.6	0.9	0.8
July	23.4	14.9	36.4	23.1	12.7	34.2	24.4	16.2	28.4	22.7	14.4	31.0	26.2	26.0	0.5	8.6
August	22.1	12.5	33.6	21.9	10.8	33.5	21.7	13.8	25.8	21.9	13.0	30.4	22.3	24.6	4.7	2.3
September	15.7	6.9	30.1	15.4	7.4	25.5	17.4	8.4	22.0	15.7	9.0	22.8	19.9	17.0	0.0	15.7

Fig. 1. The average cumulative yield in stems per m² by cultivar × transplant timing in 2018 (A, C, E) and 2019 (B, D, F) harvested from two high tunnels and a field in North Logan, UT. Blue shades represent transplant timings in high tunnels (HT): early February (EF), Early March (EM), Late March (LM), and mid-April (MA); red shades represent transplant timings in the field (F): late April (LA) and late May (LM). The vertical lines in B, D, and F represent the pruning timing within the high tunnels to promote a second flush of stems. The percent of total yield is indicated by symbols along each cultivar × transplant timing line for T²⁰ (20%, black circle), T⁵⁰ (50%, white circle), and T⁸⁰ (80%, black triangle).

marketable yields of ‘Chantilly’ were greatest from HT-EM and HT-LM timings, which annually produced 81 to 109 total and 60 to 91 marketable stems per m² (Table 2). The average total yields of ‘Potomac’ were also

greatest from HT-EM and HT-LM timings and ranged from 94 to 135 stems per m² across years, but HT-LM produced the greatest percentage of marketable stems (Table 2). For ‘Rocket’, HT-LM transplants produced

the greatest total and marketable yields of 141 (± 16 SE) and 119 (± 15 SE) stems per m², respectively, whereas those planted in HT-EA produced the greatest percentage of marketable stems (Table 2).

Across both transplant timings in the field, ‘Chantilly’ production began the earliest, with T²⁰ occurring 12 to 22 d earlier than ‘Potomac’ and ‘Rocket’ across both years (Fig. 1). The timing of T²⁰, T⁵⁰, and T⁸⁰ for ‘Potomac’ was 2 to 5 d earlier than ‘Rocket’ in 2018, but 1 to 10 d later in 2019. ‘Chantilly’ had nearly the same average total and marketable yields for F-LA and F-LM in 2018 (Table 3). In 2019, F-LA transplants averaged 254 (± 33 SE) total and 48 (± 11 SE) marketable stems per m² and F-LM averaged 152 (± 20 SE) total and 64 (± 14 SE) marketable stems per m² (Table 3). ‘Potomac’ produced greater average total yields when transplanted in F-LA than in F-LM across both years (Table 3). The average marketable yields were the same between timings in 2018, but F-LA transplants produced more than 2 times greater marketable yields (52 stems/m²) than F-LM transplants (24 stems/m²) in 2019 (Table 3). Similarly, ‘Rocket’ transplanted in F-LA produced 2.5 and 2 times greater total and marketable stems per m², respectively, than transplants from F-LM (Table 3).

Second flush. After a midsummer pruning in the high tunnel that stimulated a second flush in 2019, ‘Chantilly’ reached T²⁰ on 29 Aug., 3 d earlier than ‘Potomac’ and ‘Rocket’. ‘Chantilly’ also reached T⁵⁰ 4 to 7 d earlier and T⁸⁰ 12 to 15 d earlier than ‘Rocket’ and ‘Potomac’ (Fig. 1). ‘Chantilly’ produced a total yield of 80 (± 33) stems per m², which was significantly greater than both ‘Potomac’ with 55 (± 22) stems per m² ($P = 0.004$) and ‘Rocket’ with 52 (± 21) stems per m² ($P = 0.001$). However, the marketable yields for ‘Chantilly’, ‘Potomac’,

Table 2. High tunnel (HT) production by mean total and marketable yields in stems per m² (± SE) for ‘Chantilly’ (C), ‘Potomac’ (P), and ‘Rocket’ (R) and transplant timings early March (HT-EM), late March (HT-LM), and early April (HT-EA) in North Logan, UT, during 2018 and 2019. Significance of pairwise comparisons is indicated for each year.

Effect	Cultivar and transplant timing	Total yield		Marketable yield	
		2018	2019	2018	2019
		Stems per m ²			
Cultivar	Chantilly (C)	79 (6)	90 (6)	53 (4)	75 (5)
	Potomac (P)	101 (8)	88 (6)	62 (5)	63 (5)
	Rocket (R)	— ^z	119 (8)	— ^z	97 (7)
	C vs. P (<i>P</i> value)	0.025	0.984	0.236	0.24
	P vs. R (<i>P</i> value)	— ^z	0.017	— ^z	0.002
	R vs. C (<i>P</i> value)	— ^z	0.023	— ^z	0.055
Transplant timing	HT-EM	121 (11)	104 (7)	82 (8)	78 (6)
	HT-LM	92 (9)	114 (8)	63 (7)	95 (7)
	HT-EA	64 (6)	79 (5)	36 (8)	62 (5)
	HT-EM vs. HT-LM (<i>P</i> value)	0.113	0.571	0.207	0.184
	HT-LM vs. HT-EA (<i>P</i> value)	0.024	0.004	0.005	0.002
	HT-EA vs. HT-EM (<i>P</i> value)	0.0003	0.029	0.0001	0.095
Cultivar × transplant timing	C HT-EM	109 (14)	99 (11)	82 (12)	84 (10)
	C HT-LM	81 (10)	109 (13)	60 (9)	91 (11)
	C HT-EA	55 (7)	67 (8)	31 (4)	56 (7)
	P HT-EM	134 (17)	94 (11)	82 (12)	66 (8)
	P HT-LM	105 (13)	97 (11)	67 (10)	79 (10)
	P HT-EA	74 (9)	75 (9)	43 (6)	49 (6)
	R HT-EM	— ^z	120 (14)	— ^z	87 (11)
	R HT-LM	— ^z	141 (16)	— ^z	119 (15)
	R HT-EA	— ^z	99 (11)	— ^z	89 (11)

^z‘Rocket’ was not included in the statistical analysis for 2018.

Table 3. Field (F) production by mean total and marketable yields in stems per square meter ($\pm$ SE) by cultivars ‘Chantilly’ (C), ‘Potomac’ (P), and ‘Rocket’ (R) and transplant timings late April (HT-LA) and late May (HT-LM) in North Logan, UT, during 2018 and 2019. Significance of pairwise comparisons between treatments is indicated for each year.

Effect	Cultivar and transplant timing	Total yield		Marketable yield	
		2018	2019	2018	2019
		Stems per m ²			
Cultivar	Chantilly (C)	85 (5)	197 (18)	45 (3)	55 (9)
	Potomac (P)	105 (7)	114 (10)	80 (5)	35 (5)
	Rocket (R)	— ^z	134 (12)	— ^z	41 (7)
	C vs. P (<i>P</i> value)	0.035	0.001	0.0004	— ^y
	P vs. R (<i>P</i> value)	— ^z	0.436	— ^z	— ^y
	R vs. C (<i>P</i> value)	— ^z	0.021	— ^z	— ^y
Transplant timing	F-LA	98 (6)	209 (15)	59 (4)	53 (7)
	F-LM	91 (6)	100 (8)	56 (4)	36 (5)
	LA vs. LM (<i>P</i> value)	0.426	<0.0001	0.669	0.038
Cultivar $\times$ transplant timing	C F-LA	85 (8)	254 (33)	47 (5)	48 (11)
	C F-LM	84 (7)	152 (20)	43 (5)	64 (14)
	P F-LA	111 (10)	170 (20)	74 (8)	52 (11)
	P F-LM	98 (9)	77 (10)	74 (8)	24 (5)
	R F-LA	— ^z	211 (27)	— ^z	58 (13)
	R F-LM	— ^z	85 (11)	— ^z	29 (7)

^z‘Rocket’ was not included in the statistical analysis for 2018.

^yNo comparisons between cultivars due to an interaction with transplant timing.

and ‘Rocket’ were 40 ($\pm$ 15), 32 ($\pm$ 12), and 31 ($\pm$ 11) stems per m², respectively, which were not significantly different (*P* > 0.05). Marketable yields of the second flush were lower than the first flush by 33%, 22%, and 13% for ‘Chantilly’, ‘Potomac’, and ‘Rocket’, respectively. No statistical differences were found between transplant timings (*P* > 0.05).

Stem quality. Across transplant timings in the high tunnel for the first flush, the majority of the stems produced by ‘Chantilly’ was graded as “extra,” “fancy,” and “special” from May to June, and “utility” in July. The

majority of stems produced by ‘Potomac’ in June and July was graded as “utility” and “special,” while ‘Rocket’ was graded as “special” in June and July. During the second flush (August to September), the majority of stems graded as “utility,” “first,” and “extra” for ‘Chantilly’; “utility,” “extra,” and “fancy” for ‘Potomac’; and “utility,” “first,” “extra,” and “fancy” for ‘Rocket’ (Fig. 2). In the field, across transplant timings and cultivars, the majority of stems graded as “utility.” The second most common stem grade was “first” for ‘Chantilly’ and ‘Rocket,’ and “first” and

“extra” for ‘Potomac’. Despite differences in marketable grades, all stems sold on local markets as bunches of five stems for \$7.50 from May through September each year. About 40% of stems graded as “utility” sold at a discounted price of \$3.75 per bunch.

Shading treatment. Field production under 30% shade averaged 147 total ($\pm$ 9 SE) and 52 marketable ($\pm$ 6 SE) stems per m², while unshaded controls averaged yields of 176 ($\pm$ 23 SE) total and 47 ($\pm$ 4 SE) marketable stems per m². No significant differences were found between shading treatments for either total (*P* = 0.285) or marketable (*P* = 0.218) stem production. All cultivars reached T²⁰, T⁵⁰, and T⁸⁰ 7 d earlier in the unshaded control than in the shaded treatment. No differences were found between the percentage of stems within each grade.

Discussion

Snapdragon harvests from high tunnels began 3 weeks before the last frost date, 5 to 8 weeks earlier than field harvests, produced fewer culls, and had a greater percentage of marketable stems in the “extra” to “special” grades than the field production system. High tunnels allowed for earlier transplant timings that maximized time under cooler growing conditions, whereas sequential transplant timings staggered the T⁵⁰ peak production by up to 3 weeks in the high tunnel and 4 weeks in the field. The lack of protection from freezing temperatures in spring, high temperatures during peak production, wind, and high light intensity likely limited stem length and quality in the field, compared with the high tunnel, as was found in other studies (Ortiz et al., 2012; Wien, 2009). However, field production continued 2 to 8 weeks after marketable yields in the high tunnels declined, which allowed for an extended harvest later into summer.

In 2018, field harvests began earlier, and the percentage of marketable yields was greater than in 2019. The earlier field harvest is attributed to the warmer minimum temperatures in the field in 2018 that led to more rapid growth and floral development, whereas the lower marketable yields of 2019 are attributed to the more extreme fluctuations in air temperature that lasted from March through Sept. 2019. In particular, the superoptimal average maximum temperatures from May through July 2019, and the greater light intensity, likely led to shorter stems and lower marketability.

Selecting cultivars across maturity groups made use of the increasing temperature and daylength during the growing season to stagger and extend harvest. ‘Chantilly’ (Group I–II) generally bloomed 2 to 3 weeks earlier than ‘Potomac’ (Group III–IV) and ‘Rocket’ (Group IV) in both years across high tunnel and field production systems. ‘Chantilly’ benefited from early transplant timings, as warmer temperatures limit stem length later in summer (Wien, 2009). ‘Rocket’ generally bloomed later than the other cultivars, as is consistent with its Group IV classification and extended the production window later into July and August. Although ‘Chantilly’ has been shown to be

Fig. 2. The average yield in stems per square meter by cultivar and stem quality categorized as “utility” (shorter than 46 cm stem length), “first” (46–60 cm), “extra” (61–75 cm), “fancy” (76–90 cm), and “special” (>91 cm), harvested in 2018 (A, C) and 2019 (B, D, E). Production during the main season is given for the field (A, B) and two high tunnels (C, D) in 2018 and 2019, and the second flush is given for two high tunnels in 2019 (E) in North Logan, UT.

nearly 5 times more productive than 'Potomac' in New York high tunnels (Wien, 2013), 'Potomac' may be better suited for the U.S. Intermountain West because of its tolerance of increased temperatures and light levels. However, by late July, stems of 'Potomac' could not support the weight of the blooms, which caused curvature, a trait that reduced marketability and was also noted by Ortiz et al. (2012) and Kluza (2019) for the cultivar 'during warmer months. High tunnel yields of 'Rocket' (Group IV) produced up to 26% more stems than 'Chantilly' or 'Potomac'; similarly, in North Dakota high tunnels, 'Rocket' produced 40% more stems than 'Potomac' (Kluza, 2019).

In the field, 'Chantilly' produced significantly greater total yields than 'Potomac' and 'Rocket', but stem lengths were shorter, and hence less marketable. Wien (2013) found field transplants of 'Chantilly Velvet' produced nearly 2 times the total yield of 'Potomac Lavender', but the average stem length was also shorter (43 cm for 'Chantilly Velvet' vs. 61 cm for 'Potomac Lavender'). Shorter stems are likely the response of the earlier cultivar group to increased temperatures (Kluza, 2019). Group I–II cultivars, such as 'Chantilly', require shorter daylengths and lower temperatures than Groups III–IV and therefore likely produced significantly lower marketable yields during midsummer field production.

Multiple transplant timings further staggered the harvest window and the optimal transplant timings across cultivars were early to late March (10 to 7 weeks before the last frost date) in the high tunnel, based on total and marketable yields. The early-February transplant timing in the high tunnel advanced the initial production of 'Chantilly' by 1 week but had minimal impact on the peak yield, whereas 'Potomac' transplanted in early February and early March bloomed at nearly the same time. Therefore, Group I–II cultivars may present an opportunity to transplant in early February, but Group III–IV cultivars are not recommended due to their higher temperature and longer daylength requirements for floral initiation.

Early-April high tunnel transplants matured under warmer conditions, which reduced the total and marketable yields of 'Chantilly' by 33% to 62% and 'Potomac' by 20% to 48%, compared with those transplanted in early March. Conversely, 'Rocket' transplants from early April were only reduced by 0% to 18%, suggesting a higher adaptability of this cultivar to higher temperatures. Previous research found no significant differences in yield or stem length between 'Potomac Red' transplanted in early March vs. mid-April in a high tunnel (Zhao et al., 2014), but this trial was conducted in USDA Hardiness Zone 8 and reinforces the need for regional trials to determine optimal transplant timings based on local climatic conditions.

The second flush in the high tunnels increased the annual yield in 2019, but stem quality grades were lower than those from the first flush. 'Chantilly' produced the greatest total yield during the second flush, and this is attributed to its lower optimal temperature requirements than the 'Potomac' and 'Rocket'. A similar trend occurred in Indiana, where spring-

transplanted 'Rocket Red' produced 90% more stems per square meter than fall-transplanted 'Potomac Orange' in the high tunnel (Ortiz et al., 2012). Future research that explores extending a second flush into October (i.e., past the first frost date) and the impact on yield is recommended, as the spread of snapdragon rust (*Puccinia antirrhini*) ended this trial on 27 Sept. As a cool-season crop, snapdragons have potential for fall markets and can be particularly profitable when an established root structure has developed from summer production and minimal additional material or labor costs are needed (Lewis et al., 2020).

Although other studies have shown shading to both delay initial bloom timing and increase stem length, compared with non-shaded snapdragons (Alhajhoj and Munir, 2016; Li et al., 2017), the shading treatments in the field production system had no significant effect on total and marketable yields or harvest timing in North Logan, UT. The lack of significance for shade in this study may be due to low statistical power to analyze interactions between shading, cultivars, and transplant timings because there were only two replicates between shade and unshaded treatments. The lack of significance may also be due to the presence of strong canyon winds, as wind has been shown to result in shorter stem lengths in the field, compared with protected high tunnel environments (Wien, 2009). Future research that explores shade with greater replication or isolated the effect of wind may help further evaluate the potential for the use of shade in the region.

Conclusion

The variation in stem length and quality between cultivars and across harvest dates would suggest price differences throughout the year according to snapdragon wholesale market history that is reported nationally. However, local markets did not support price variation by marketable grade. Regardless of marketable stem length, bunches of five consistently sold for \$7.50, the equivalent of the maximum wholesale price for long to extra-long stems (USDA Agricultural Marketing Service, 2019), indicating a strong and consistent market demand for local production and more relaxed standards for quality based on stem length. However, sellers and florists also showed preference for stem lengths between 60 and 76 cm, which were less prone to breakage during storage, transport, and floral arranging, and stems that were stored upright to prevent curvature. Therefore, continued, local production of stems that are 60 cm or longer, which can be trimmed to the marketable length and are minimally curved, can supply a niche market in high demand.

This can be achieved by local growers by transplanting 'Chantilly' in early February to late March and 'Potomac' and 'Rocket' in early to late March in high tunnels, and 'Potomac' and 'Rocket' in the field during late April. Using a second flush in fall, rather than a second planting, resulted in lower marketable

yields than the first flush but also in lower material and labor costs that both improved net returns and lengthened the production window by 2 months. Growers should weigh the potential of a second flush with alternative crops or replanting and the length of their growing season to maximize profits within a high tunnel space. The season-long evaluation of snapdragons as a cut flower provides a foundation for cultivar selection based on optimal performance times that lengthen the harvest window and improve production opportunities in supplying local, specialty crop markets.

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