EVALUATION OF HIGH TUNNEL AND FIELD PRODUCED SPECIALTY CUT FLOWERS IN THE NORTHERN GREAT PLAINS

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Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

The demand for local sustainably grown produce and flowers has increased (Low et al., 2015), and stimulated a growing interest in high tunnel production. The goal of this research project was to evaluate the production of cut flowers in high tunnel structures and in the field in the Northern Great Plains (NGP) region. The NGP offers unique climatic and environmental challenges based on its continental climate. Specialty cut flower cultivars Karma Irene and Chocolate dahlia (*Dahlia x hybrida*), Potomac White and Rocket Mix snapdragon (*Antirrhinum majus*), and Mariachi Misty Blue, Echo Blue and ABC2 lisianthus (*Eustoma grandiflorum*) were planted in both field and high tunnel environments at two soil temperature setpoints in the NGP to determine which of the selected crops are best suited for cut flower production. Our results indicate higher yields and more consistent quality in the high tunnel; however, the field was suitable for all species investigated.

ACKNOWLEDGEMENTS

Thank you, to my friends who I consider my family. Without the love and support of Jack, Maddie, and Bayan North Dakota winters would have been unbearable. To Peter, Payton, Brent, Matt, Maxwell, Nikki, and Evan, whose friendship followed me to Fargo and beyond, I’m eternally grateful. Thank you, High Value Crops team – David Mettler, Abby Debner, Jorden Hinrichsen, Austin Espe, John Stenger, Lindsey Forward, Kyla Splical, Collin Auwarter, and everyone else, for the blood sweat and tears that went into this project. Thank you to my committee – Drs. DeSutter, Hatterman-Valenti, and Lee- for working so diligently to make sure both I and this research project were successful. Finally, thank you Dr. Esther McGinnis, for your unwavering determination, caring, and understanding, all of which is the reason I am here today.

DEDICATION

This thesis is dedicated to Drs. Ferris and Zlesak who inspire others every day, Pamela Weller whose memory and bravery I cherish, and Emily Balder the person I hold dearest in this life.

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16A	2016 Environment Absaraka, ND
16W	2016 Environment Williston, ND
17A	2017 Environment Absaraka, ND
17W	2017 Environment Williston, ND
‘ABC’	Lisianthus Cultivar ABC Blue
ADT	Average Daily Temperature °C
‘Choc’	Dahlia Cultivar Karma Chocolate
D/N	Day/Night
DIF	Day/Night differential °C
DLI	Daily light integral (mol·m^{-2}·d^{-1})
‘EB’	Lisianthus Cultivar Echo Blue
GDU	Growing Degree Units °C
‘Irene’	Dahlia Cultivar Karma Irene
MAX	Maximum Daily Temp °C
MIN	Minimum Daily Temp °C
‘MMB’	Lisianthus Cultivar Mariachi Misty Blue
‘PW’	Snapdragon Cultivar Potomac White
‘RM’	Snapdragon Cultivar Rocket Mix
Stems m^{-2}	Stems per meter squared

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LITERATURE REVIEW

Current Floriculture Market

In the U.S., consumers purchased an estimated $17 billion of floriculture products in 2015 (Prince and Prince, 2016). Production in California and Florida account for 75% of all domestically grown cut flowers in the U.S. (Bonarriva, 2003). It is estimated 30% of U.S. households annually purchase fresh cut flowers and greens (Hall, 2006). Foreign imports dominate the U.S. flower market, sometimes accounting for 90% or more of all U.S. sales (Bonarriva, 2003). In 2016, $1.4 billion of cut flowers were imported and this is expected to increase in the future (Prince and Prince, 2016). Domestic producers find it hard to compete with foreign imports due to higher energy, land, and labor costs than their international competitors (Porter and Van Der Linde, 1995). Colombia and Ecuador are the dominant producers of roses (*Rosa hybrida* L.), carnations (*Dianthus caryophyllus* L.), florist's chrysanthemum (*Dendranthema x grandiflorum*), and Peruvian lily (*Alstroemeria* spp. L.) for the U.S. cut flower market. Both countries have exceptional climates for commercial growing, relatively weak currencies, and tax incentives to support their niche market (Dole and Greer, 2004). Almost 85% of total U.S. imports of cut flowers since 2001 entered duty free under preferential trade programs (Bonarriva, 2003). The majority of those imports entered under the Andean Trade Preferences Act that benefits Bolivia, Colombia, Ecuador, and Peru (Dole and Greer, 2004). Holland, Mexico, and Costa Rica also export significant amounts of cut flowers to the US (Bachmann, 2006).

International growers focus their crop production efforts on mass production, shipping and handling concerns, high demand items, and species that require smaller climate control investments (Bachmann, 2006). These advancements have led to an increased global supply of fresh cut flowers. Since the early 1990s, fresh cut flower import prices have fallen significantly (Bonarriva, 2003). In the face of increased competition, many U.S. growers have shifted production to specialty cut flowers or high-end novelty species that are not easily stored and shipped long distances (Armitage and Laushman, 2003).

Northern Great Plains Climate

The Northern Great Plains (NGP) are located in the center of the North American continent and are subdivided into four main physiographic regions: Great Plains, Glaciated Plains, Missouri Coteau, and the Red River Valley (Enz, 2003). The NGP is typically divided into two distinct regions, from the mesic eastern section to the semi-arid western section (Frankson et al., 2014). In Absaraka, representative of the eastern climate, annual average precipitation over the last 30 years equaled 60.1 cm with average growing degree units (GDU) with base 13°C of 810 units from May to November. GDU is a way of assigning a heat value to each day. The values are added together to give an estimate of plant seasonal growth (Miller et al., 2001). Percent of possible sunshine is 70 to 75% during July and August, and averages about 60% for the entire year (National Oceanic and Atmospheric Administration, 2013). In Williston, representative of the west, annual average precipitation over the last 30 years equaled 36.3 cm with average GDU with base 13°C of 983 units from May to November. Percent of possible sunshine is 80 to 87% during July and August, and averages about 75% for the entire year (National Oceanic and Atmospheric Administration, 2013).

The major limiting factor in agricultural production in the NGP is the length and severity of winter and the shortness of the growing season. Winters are characterized by below freezing temperatures and snowfall. Snow is the main form of winter precipitation, but freezing rain, ice, sleet, and sometimes even rain are all possible during the winter months. Temperatures as low as −51°C have occurred. Growing season length is typically defined as the amount of frost-free days (> 0°C) during a year (Kunkel et al., 2004). On average Williston experiences 130 days frost free with the average last and first frost dates of May 11th in the spring and Sept. 18th in the fall.

Absaraka experiences 139 days frost free with the average last and first frost dates of May 10th in the spring and Sept. 26th in the fall (NOAA., 2013).

Cut Flower - High Tunnel Production

Since the early 2000s, greenhouse production of cut flowers has shifted to less expensive structures such as high tunnels or to field production (Armitage and Laushman, 2003). High tunnels are unheated, passive-solar greenhouse structures used to alter the crop environment. These structures provide protection from extreme environmental conditions and exclude animals (Knewtson et al., 2010). The absence of rainfall results in fewer diseases (Wien, 2009). Growers also use high tunnels for season extension and to enhance crop quality and yield (Lamont et al., 2002). Season extension research found that high tunnels in the northeastern region of the U.S had on average 21 additional growing days when compared to field production, but did not find a correlation between high tunnel production and increased duration of harvest season (Wien, 2010).

Little research on season extension in specialty cut flower production has been conducted, with most research concentrating on yield and quality. Ortiz et al., (2012) found cut flower stems harvested from the high tunnel were significantly longer than stems harvested from the field for snapdragons, lisianthus, stock plant *(Matthiola incana* L.*)*, and zinnia (*Zinnia elegans* Jacquin). Additionally, the number of stems harvested per unit area was significantly increased in the high tunnel compared to the field for snapdragons, celosia (*Celosia spicata* [Thouars] Sprengel), carnations, and zinnia. Continuing research found that when compared with field-grown crops, high tunnels generally improved yield, quality, and marketability of cut flowers (Owen et al., 2016). When crop productivity was compared on a per unit time basis, high tunnel cut flowers produced more stems per week than those grown in the field (Wien, 2009). Owen et al. (2016) reported that, the total number of celosia and bells of Ireland (*Moluccella laevis* L.) stems harvested from the high tunnel was significantly greater, when compared with those harvested from the field. However, this finding did not extend to dianthus, matricaria {*Tanacetum parthenium* [Linnaeus] (Schultz Bipontinus)}, and snapdragon. High tunnel production offers several benefits over field production when growing high-quality specialty cut flowers. However, the benefits associated with high tunnel production are cultivar-specific and environment specific, because overall stem quality is a culmination of several characteristics (Ortiz et al., 2012).

Cut Flower - Field Production

There has been a recent resurgence of interest in the production of field-grown specialty cut flowers. Specialty cut-flower species grow in a wide range of climatic conditions. This provides growers in all regions with an opportunity to select crops well-adapted to their environmental conditions. Field production systems offer one main benefit over other systems and that is limited input of resources. Previous research concentrates on productivity and profitability in the forms of yield and stem quality in a limited number of fields grown cut-flower species. Such production techniques have included spacing (Armitage, 1987), successive planting dates (Armitage and Laushman, 1990), shading (Armitage, 1991), and fertilizer application rate (Paparozzi and Hatterman, 1988).

Research Objectives

1 Evaluate dahlia, snapdragon, and lisianthus cultivars as specialty cut flowers under both high tunnel and field production systems in the NGPs.

2 Compare soil transplanting temperatures of 13 and 18°C to assess early season extension.

3 Determine the production density per square meter of high tunnel and field production systems.

CHAPTER I. EVALUATION OF HIGH TUNNEL AND FIELD GROWN DAHLIA AS A SPECIALTY CUT FLOWER IN THE NORTHERN GREAT PLAINS

Introduction

Dahlia (*Dahlia* x *hybrida* Hort.) is a popular cut flower, bedding, and potted plant because of its diversity of forms, colors, sizes, and textures (Runger and Cockshull, 1985; Salunkhe et al., 1990). Dahlia is becoming an emerging staple of the U.S. floriculture industry rather than the import market due to complex phenological requirements and the labor/resources needed to meet these requirements (Hankins, 2005). Dahlia originates from Mexico and its overall maturation cycle alternates between periods of rest (dormancy), vegetative growth, and flowering (Konishi and Inaba, 1967). At temperate latitudes, growth and reproduction are determined mainly by temperature, light intensity, and photoperiod. The conventional method of growing dahlia as a tender geophyte mimics the natural phenology. Tuber clusters are dug in the late fall, one week after the first killing frost (Konishi and Inaba, 1967). The tubers are stored over winter in a protected environment at 4.4 to 7.2°C. This is to meet the requirement for a 6 to 8-week cold treatment to overcome dormancy in tuber propagation (Nau, 2011). Tuberous root development and flower induction of dahlia are controlled by photoperiod and light intensity (Brøndum et al., 1993).

Morphology

For any given latitude, photoperiod (day length) and light intensity vary significantly through the year as the sun's path in the sky changes with time. Light intensity is defined as an instantaneous measure of photosynthetically active radiation which is measured in wavelengths between 400 and 700 nm (Torres and Lopez, 2010). Changes in photoperiod are evident with changing seasons (Appendix B1). Taken together, the daily light integral (DLI), measures light intensity and duration per unit area (Torres and Lopez, 2010).

Konishi and Inaba, (1964, 1966) found the optimum photoperiod for dahlia flower induction and initiation to be less than 12 hours. In contrast, long days (greater than 12 hours) are required to complete floral development. Dahlia plants continuously exposed to 10-h photoperiods during floral development had a high percentage of aborted flower buds (Halburton and Payne, 1978). While long days delayed floral induction and initiation, the application of long-day photoperiods during floral development improved flowering percentage and overall flower and foliage quality (Legnani and Miller, 2001). The time to flower initiation decreases rapidly as DLI falls below 20 $mol \cdot m^{-2} \cdot d^{-1}$ (Langton, 1992). Increasing above this threshold appears to have little additional effect on the time to flowering. These results collectively indicate a relatively narrow set of conditions for optimal flowering, with optimal defined as fast-developing plants with many flower buds and uniform plant height. Vegetative growth and maturation require 12 to 14-h photoperiods at temperatures between 15 to 20 °C. Photoperiods less than 12 h promote tuberous root formation and inhibit vegetative and reproductive shoot growth and should be avoided. Similarly, a temperature of 15 °C promotes tuberous root formation, while temperatures of 25 °C or higher reduce or prevent flowering entirely (Brøndum et al., 1993).

Scientific research on dahlia production in either the field or high tunnel is scarce in the US and abroad. In 2012, Ortiz et al. found that ‘Karma Thalia Dark Fuchsia’ produced flowers with comparable stem length, stem caliper, and flower width in the field and high tunnel. The number of stems per unit area for dahlia was not reported. Beyond that, no other research could be found pertaining to dahlia cut flower production in the field or a high tunnel system. The lack of published research combined with the fact that dahlias have such a relatively narrow set of conditions for optimal growth make it difficult to optimize production in any environment. Therefore, the objective of this study was to evaluate the production of two different dahlia cultivars under field and high tunnel systems in the NGP climate. Dahlia cultivars should be evaluated further for all regions of the US, including NGP, to ensure the competitiveness of domestic specialty cut flowers.

Materials and Methods

Two independent but identical field and high tunnel experiments were carried out at two locations in North Dakota (that approximate two distinct east and west regions in the NGP) during the years 2016 and 2017. The eastern location was located at the Dale E. Herman Research Arboretum near Absaraka, ND (46°59'27.9" N and 97°21'20.1" W ("Absaraka")). The western location was at the Williston Research Extension Center's Nesson Valley Irrigation Research Site near Williston, ND (48°09'46.3" N and 103°06'29.4" W ("Williston"). The experiment evaluated two cultivars, Karma Irene and Karma Chocolate ('Irene' and 'Choc') (Germania Seed Company, Chicago, IL, USA), under two soil transplanting temperatures (13 and 18 °C). On 14 April 2016 and 21 April 2017, respectively, rooted dahlia cuttings were received and transplanted within 7 d into 606-deep cell packs (205 mL individual cell volume, T.O. Plastics, Clearwater, MN, USA) filled with a commercial soilless medium (PRO-MIX BX Mycorrhizae; Premier Tech Horticulture, NB, CA). Plant material was maintained in a glass-glazed greenhouse with forced air heating at day/night (D/N) temperatures of 21±3°C /18±3°C. Supplemental light using high pressure sodium lamps (GE Ecolux-1000, GE Lighting Solutions LLC, Cleveland, OH, USA) on a 12-h D/N cycle was controlled by an environmental control system (Maximizer Precision 10; Priva Computers, Vineland Station, ON, CA) at North Dakota State University in Fargo, ND.

High Tunnel and Field Environments

Plants were transplanted based on daytime average soil temperatures of either 13 or 18 °C, in their respective production environments (Table 1). In 2016, the transplanting dates ranged from 20 May to 10 June. Transplanting dates in 2017 began on 24 April and continued until 2 June.

Table 1. Dates Associated with Soil Temperature Setpoints for Transplanting in the Field and High Tunnel Production Systems in Four Environments (Location by Year) in the Northern Great Plains

	Soil Temperature	Environments			
		16A	17A	16W	17W
High Tunnel	13°C	20-May	24-Apr	25-May	26-Apr
	18°C	30-May	6-May	10-Jun	11-May
Field	13°C	25-May	17-May	2-Jun	26-May
	18°C	8-Jun	29-May	10-Jun	2-Jun

Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston.

Both high tunnels (30 m long, 9 m wide, 5 m tall) were constructed with a triple-galvanized structural steel frame and were covered with 6 mm exterior polyethylene film and a 4 mm polyethylene interior film with tri-layer construction and ultraviolet additives that allowed 90% light transmission (Rimol Greenhouse Systems, Hooksett, NH, USA). Activated by temperatures, automated end-wall peak vents (21.1 °C) and roll-up sidewalls (26.6 °C) provided most of the ventilation. Two large garage doors located on both end walls provided additional ventilation when needed. The sidewalls were raised during periods of high winds. The soil for the Absaraka experiments is from the Warsing series (fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Oxyaquic Hapludolls) containing 1.2% organic matter and a pH of 7.2. The soil for the Williston experiments is from the Bowdle series (fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Pachic Haplustolls) with 2.1% organic matter and a pH of 7.0. A total of ten beds (13.7 m long, 1 m wide) at each site were constructed in a north-south orientation, five in the field and five in the high tunnel. All 10 beds were broadcast fertilized using 20-10-20 with micronutrients (JR Peters Inc., Allentown, PA, USA) at a rate of 84 kg·ha-1. A 0.4 mm thick drip watering system with 20.3 cm emitter spacing and 4.5 x 10-5 m3·s-1 flow rate was installed in each plot (Aqua-Traxx; The Toro Company, Bloomington, MN, USA). Each plot with two plant rows had three individual lines to provide water effectively and efficiently. Each sub-plot was run on an individual timer and solenoid valve to optimize water usage.

Data Collection

Resistance-based temperature sensors (External Temperature Sensor; Spectrum Technologies, Inc., Plainfield, IL, USA), enclosed thermocouples, and conductivity sensors (GS3 Soil Moisture, Temperature and Electrical Conductivity Sensor, Meter Group, Inc. Pullman, WA, USA) recorded soil and air temperature and soil water volume respectively, every 30 s and averages were calculated every 5 min by a data logger (Watch Dog Model 2475-Plant Growth Station; Spectrum Technologies, Inc, Aurora, IL, USA). Each whole plot received its own data logger with five sensors spaced out evenly in a circular pattern from the center. Each sensor chosen was tested then calibrated to reduce variation. All DLI measurements were plotted for each environment from data collected at the North Dakota Agriculture Weather Network stations near the respective sites. Growing degree units (GDU) were calculated from air temperature data collected and calculated using base 13 °C (average daily temperature °C (ADT) – 13 °C) where ADT (°C) = (maximum daily temp °C (MAX) + minimum Daily Temp °C (MIN)) (Romo and Eddleman, 1995). Average daily temperature, MAX, MIN, and day/night differential (DIF) were derived from temperature data collected in their respective environments. Morphological data collected included flower number, stem length, and stem caliper from stems harvested twice a week. Stem marketability was determined by length (greater than 30 cm), caliper (greater than 4 mm) and flower quality (no visual damage) (Barr, 1992).

Experimental Design and Statistical Analysis

Each experiment was laid out in a randomized complete block design with a split-split plot in time arrangement. The experiments investigated environmental (location by year) differences (whole plot factor A), two cultivars (factor B sub-plot), and two soil transplanting temperatures (factor C sub-sub-plot). Environments were represented by year (2016 or 2017) and location (A for Absaraka and W for Williston). Each experimental unit was 1 m x 2.75 m and contained eight plants spaced 60 cm apart with a total area of 2.75 m2 with four replications. Average number of stems will be reported on a square meter basis to allow comparisons to previous studies. Data was analyzed with SAS (SAS 9.4, SAS Institute, Cary, NC, USA) General Linear Mixed Model (PROC GLMM) using the Auto-Recursive 1 structure.

Results

Average Number of Stems Per Square Meter

Results were analyzed separately for high tunnel and field production. In the high tunnel, the main effect of environment (location by year, factor A) was significant for average number of stems. For field-grown dahlias, two interactions occurred between cultivar (factor B) and environment, as well as temperature (factor C) and cultivar for average number of stems (Appendix A1). In the high tunnel, more dahlia stems were harvested in 2017 Absaraka and Williston environments than in the 2016 Absaraka and Williston environments (Figure 1).

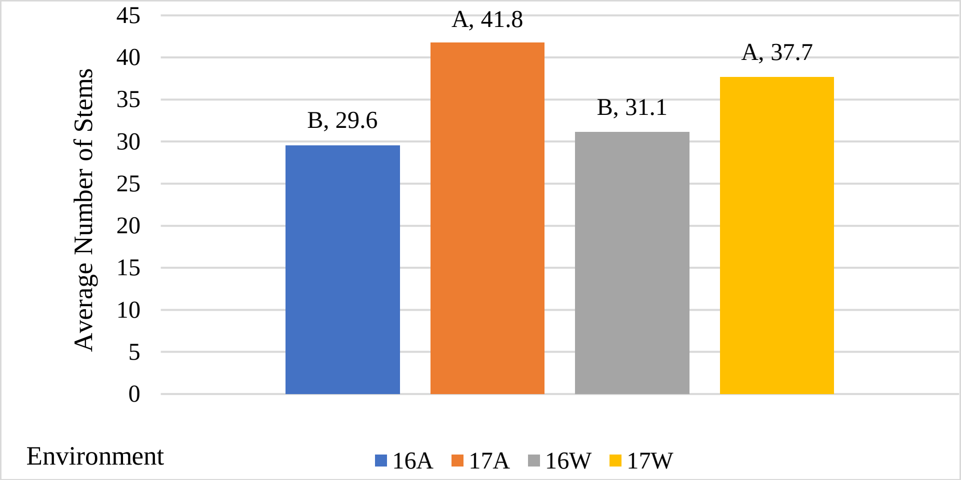

Figure 1. Main Effect of Environment (Location by Year) on Average Number of Stems per Square Meter Produced in the High Tunnel. Mean number of stems with a common letter are not different ($P \leq 0.05$) by Tukey's HSD test (n= 3). Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston.

For field-grown dahlias, 'Irene' produced on average more stems within the Absaraka environment in 2017 compared to the other three environments (Figure 2). In 2017 Absaraka, 'Irene' yielded more stems (21.5) than 'Choc' (13.3), a 61% increase. 'Irene' generated more stems than 'Choc' in both years at Williston. In Williston, both cultivars yielded significantly more flower stems in 2017 compared to 2016. No significant differences between cultivars were observed in 2016 Absaraka. In 2016 Williston, 'Choc' had the fewest stems harvested compared to 'Irene'.

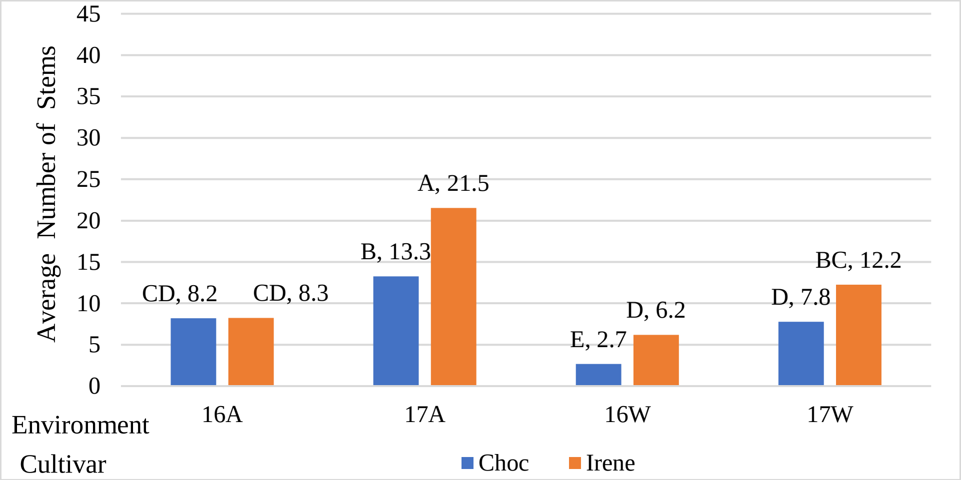

Figure 2. The Effect of Cultivar and Environment (Location by Year) on Average Number of Dahlia Stems per Square Meter Produced in the Field. Mean number of stems with a common letter are not different ($P \leq 0.001$) by Tukeys HSD test (n= 3). Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston.

When transplanted into 13 °C soils in the field, 'Irene' produced more stems (13.5) compared to the warmer soil transplanting temperature of 18 °C (10.5). In contrast, soil temperature did not affect stem production for 'Choc' (7.8 to 8.1 stems) (Figure 3). At both temperatures, 'Irene' yielded more stems compared to 'Choc'.

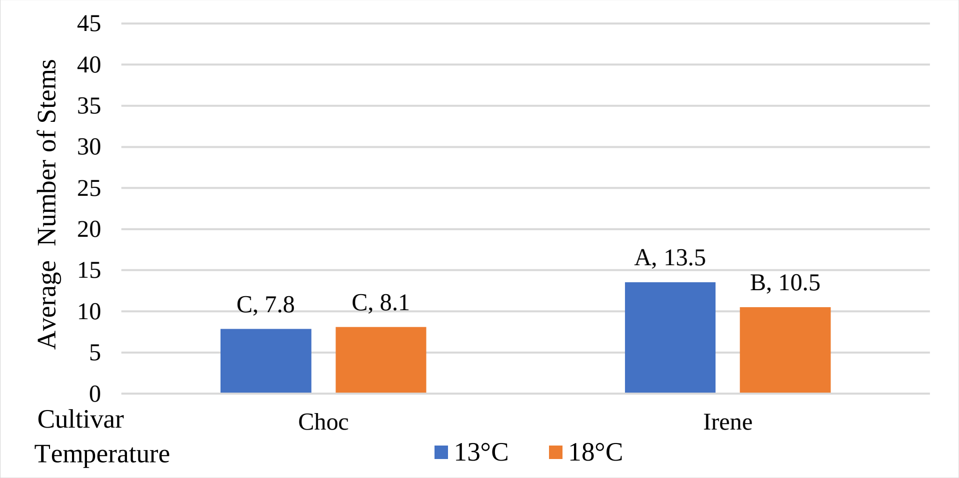

Figure 3. The Effect of Cultivar and Soil Transplanting Temperatures on Average Number of Dahlia Stems per Square Meter Produced in the Field. Mean number of stems with a common letter are not different ($P \leq 0.01$) by Tukeys HSD test (n= 2). Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston.

Average Stem Length

Factor A, environment, was significant for average stem length in the high tunnel, while the three-way interaction between temperature, cultivar, and environment was significant for stem lengths in the field (Appendix A1). Stem lengths for dahlia cut flowers grown in the high tunnel in Absaraka in 2017 as well as Williston in both years were similar, with production ranging from 35.5 to 49.0 cm in length, well above the minimum marketable length of 30 cm (Figure 4). Plants in the 2016 Absaraka environment produced shorter stem lengths averaging 23.4 cm, well below stem length standards.

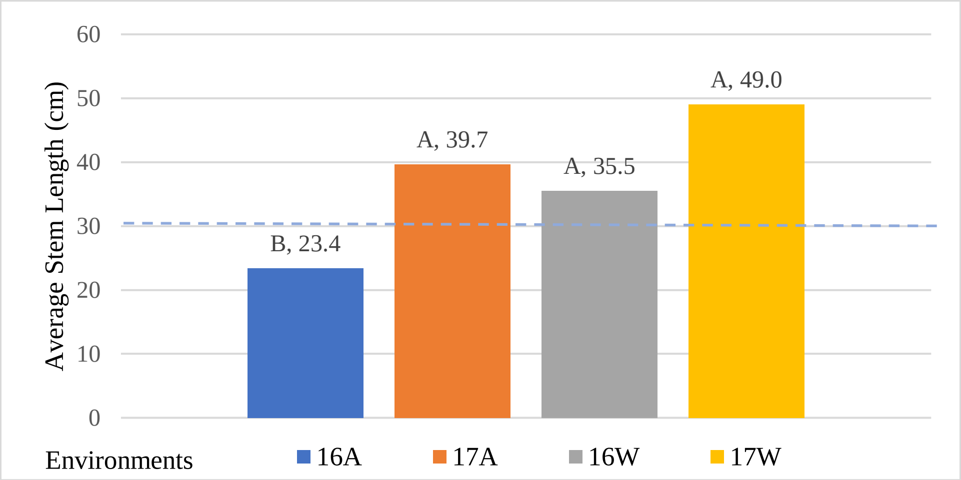

Figure 4. The Effect of Environment on Average Stem Length of Dahlias Harvested in the High Tunnel. Mean stem lengths with a common letter are not different ($P \leq 0.01$) by Tukeys HSD test (n= 3). Blue dotted line represents minimum length required for marketability (30 cm) (Barr, 1992). Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston.

Only one cultivar in one environment displayed a sensitivity to soil temperature at transplanting in the field (Figure 5). When transplanting was delayed to 18 °C in 2016 Williston, ‘Choc’ had shorter stem lengths, an 18% decrease compared to transplanting at 13 °C. When examining ‘Choc’ at 13 °C in 2016 Absaraka, stem lengths were shorter (15 cm) and below market quality, compared to the remaining environments of ‘Choc’ at 13°C. Average stem lengths in those environments ranged from 34.9 to 41.3 cm. Stem lengths for ‘Irene’ were similar at the environmental level for both transplanting temperatures. Regardless of cultivar, both locations in 2017 exceeded the minimum marketable stem length ranging from 34.5 to 38.1 cm, but fell short in 2016 ranging from 18.6 to 21.3 cm.

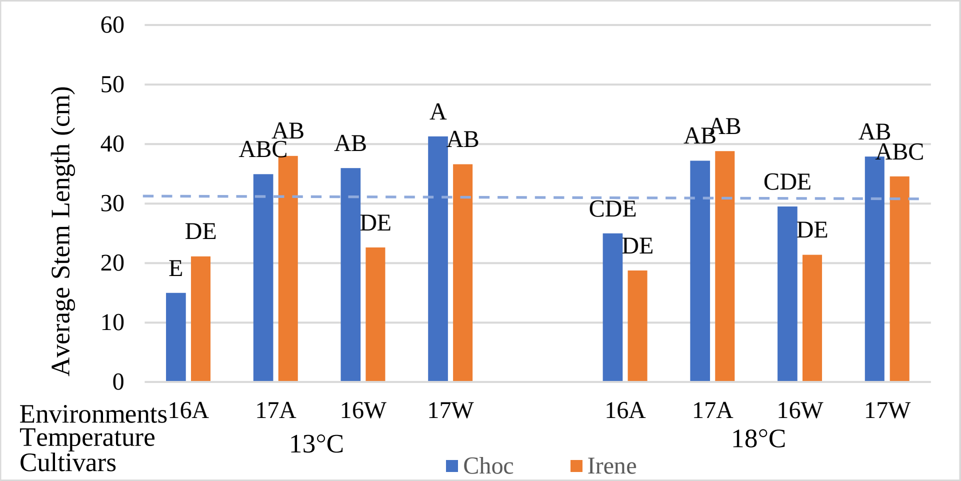

Figure 5. The Effect of Environment (Location by Year), Soil Transplanting Temperatures, and Cultivars on Average Stem Length of Dahlias Harvested in the Field. Mean stem lengths with a common letter are not different ($P \leq 0.05$) by Tukeys HSD test (n= 3). Blue dotted line represents minimum length required for marketability (30cm) (Barr, 1992). Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston.

Average Stem Caliper

The main effect of soil temperature at transplanting and the interaction between cultivar and environment were significant for average stem caliper in the high tunnel. No significant main effects or interactions occurred for stem caliper in the field (Appendix A1). When grown in the high tunnel, plants transplanted into 18 °C soil produced stems with an average caliper of 8.2 mm, a 10% increase over transplanting at 13 °C which produced an average caliper of 7.5 mm (Data not shown). Both cultivars in the two Absaraka environments and the 2016 Williston environment produced stems with similar caliper size (Figure 6). The cultivars grown in the 2017 Williston environment had significantly larger stem calipers than other environments; however, the average stem caliper for ‘Choc’ (12.2 mm) was greater than the caliper for ‘Irene’ (10.4 mm). All stem caliper averages greatly exceeded the minimum market standard. The overall average stem caliper in the field was 6 mm, well above minimum market standards (data not shown).

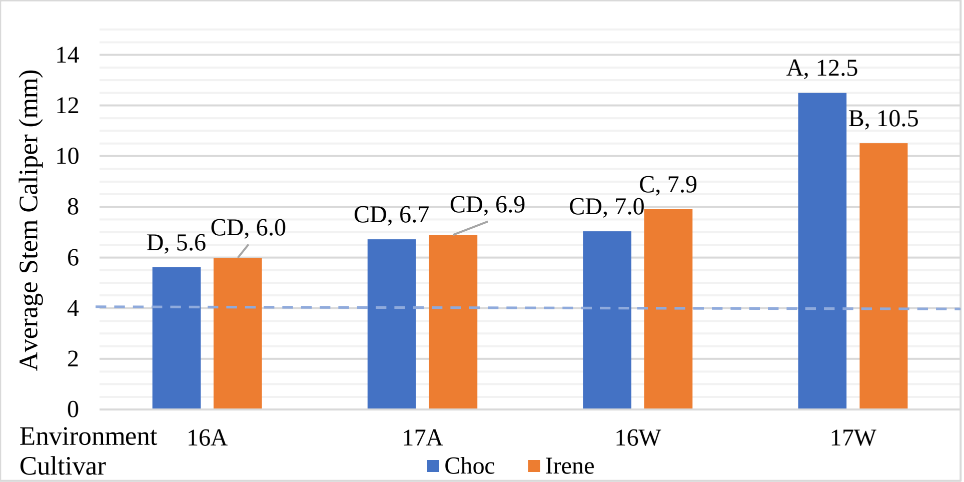

Figure 6. The Effect of Environment (Location by Year), and Cultivar on Average Stem Caliper of Dahlias Harvested in the High Tunnel. Mean totals with a common letter are not different ($P \leq 0.05$) by Tukeys HSD test (n= 3). Blue dotted line represents minimum caliper required for marketability (4mm)

Discussion

High Tunnel

Average number of stems harvested in both high tunnels, ranged from 30 to 40 stems for dahlias, depending on year. This could suggest that location within the NGP region has little to no effect on total production. Instead, yearly variations in climate may be responsible for the differences in the high tunnel. In 2016, overall production was less than in 2017, and one possible cause is that both high tunnels were constructed on 26th to the 30th of April in 2016, reducing early season heating, compared to the 2017 environments, which were able to capitalize on the benefits of passive solar heating earlier in spring. This is evident when examining planting dates from 2016 to 2017 in all environments (Table 1) as well as GDU and ADT (Appendix B2, A2). On average in 2017, the dahlias were transplanted 24 to 30 d earlier than in 2016, with an additional 182 to 353 GDU with an average 11% increase in ADT.

Average stem length in three out of four environments were above marketable lengths. In 2016 Absaraka, lengths were reduced by 50-100% compared to the other environments. Several growing conditions are known to affect stem elongation and therefore stem length, such as temperature, light intensity, light quality, photoperiod, relative humidity, CO2 concentration and plant density (Carvalho et al., 2006). Brondum and Heins (1993), report that primary shoot length of dahlia appears to be controlled by the interaction of temperature in the form of day/night temperature differential and photoperiod. Day/night temperature differential (DIF) refers to the difference between the highest daytime temperature and the lowest nighttime temperature. They reported that primary shoot length increased from 88 to 139 mm as DIF increased from -16.2°C (warmer nights) to 14.8 °C (warmer days). Temperature and photoperiod interacted to influence lengths, as temperature increased from 20°C to 30°C primary shoot length increased as photoperiod increased. At 30 °C, photoperiod had no effect as shoot elongation was minimal(Brøndum et al., 1993) . The average DIF for 30 days after transplanting was 11.1 to 12.4 °C for all environments (Appendix A3). Further examination revealed that DIF in 2016 Absaraka during late summer was reduced ~70% to approximately 4°C, vastly different from other environments which averaged a DIF of 14.6 °C. This suggests that reduced temperature differential in the high tunnel may adversely affect the production of marketable dahlia stems. A similar experiment conducted by Ortiz et al. (2012) reported that for ‘Karma Thalia Dark Fuchsia’ stem lengths averaged 34.1 cm. Apart from Absaraka environment in 2016, our results from the current study agree with the previous work.

The main effect of soil transplanting temperature was significant for average stem caliper, with a warmer soil temperature resulting in 10% thicker stems even though plants transplanted under both temperatures exceeded the market standard minimum of 4 mm. On average, dahlias transplanted at 18 °C soil temperature, had 118 lower GDU. When averaged over all the environments the average air temperature in the first 30 days after transplanting for the 13 °C soil transplanting temperature was 23.1 °C and 23.9 °C for 18°C. Research into environmental effects on stem caliper is extremely limited. Ortiz et al. (2012) reported that for ‘Karma Thalia Dark Fuchsia’ produced in the high tunnel, average stem caliper was 5.8 mm. Stem caliper in the current study increased 25-43 % compared to results by Ortiz et al. (2012).

Field

For average number of stems, differences emerged because of interactions with environment and temperature. ‘Irene’ responded adversely to a warmer soil temperature at transplanting, producing 28% fewer total stems when transplanting was delayed from 13 to 18 °C, while ‘Choc’ displayed no such response. Examining GDU and planting dates for field production we see that transplanting at 18 °C delayed planting from 7 to 10 d, with a difference of 60 to 113 GDU. This is less than the range from the high tunnel experiment, which saw no response to soil temperature at transplanting. However, the high tunnels accumulated between 1413 to 1718 GDUs over all the environments, while the field ranged from 733 to 836 GDUs (Appendix B2). This suggests that for ‘Irene’, when growing in colder environments such as the field in NGP, maximizing GDU is imperative while in the high tunnel, excess amounts of GDU accumulated over the season appear to overcome any initial differences in soil temperature.

Production was variable for both cultivars between the environments when comparing 2016 and 2017 GDUs (Appendix B2) to the 30-year averages for both locations. We see that 2016 Absaraka was similar to the 30-year average, while 2017 Absaraka, 2016 Williston, and 2017 Williston were slightly below normal (Appendix A4, A5). ‘Irene’ produced on average a significantly larger number of stems in 3 out of 4 environments compared to ‘Choc’, with the remaining environments being similar. Production ranged from 10 to 21 stems for ‘Irene’ and between 3 to 10 stems for ‘Choc’. This result coupled with ‘Irene’ producing more stems than ‘Choc’ even when planting was delayed to 18°C, suggest that ‘Irene’ is more adaptable in field environments than ‘Choc’ with regards to stem production. ‘Choc’ displayed a response from delayed transplanting from 13 °C to 18 °C in only one environment, with average stem lengths falling from marketable to unmarketable lengths. The other environments followed the same yearly trend as ‘Irene’ with marketable stem lengths being produced in only 2017. No effects were significant for caliper overall regarding averaging market quality.

Season Extension

When examining daily MIN air temperatures, the field systems experienced 142 to 147 frost free days (> 0°C), while the high tunnels experienced 199 to 205 frost free days (Appendix A3). Comparing the field environments to the 30 year average for frost free days (139) (NOAA, 2013), the number of frost free days were slightly higher, but fell within the normal range. In contrast, the high tunnels on average experienced 58 more frost free days than the field. With an average last frost date of April 19, the high tunnels experienced an extended season of 22 days in the spring and 36 in the fall. Examining the photoperiods and DLI, during the extended portions of the season in the spring, the photo period was between 13:48-14:52 hours in length (Appendix B1), well within the long days (greater than 12 hours) that are required for complete floral development as noted by Halburton and Payne, in (1978). The average DLI was between 29 to 35 $mol \cdot m^{-2} \cdot d^{-1}$ (Appendix A2) above the 20 $mol \cdot m^{-2} \cdot d^{-1}$ threshold which Langton, in (1992) identified as a threshold below which time to flower initiation decreases, negatively affecting yield and quality of production. During the fall, the average DLI over all environments was 23 $mol \cdot m^{-2} \cdot d^{-1}$ which declined quickly to 10 $mol \cdot m^{-2} \cdot d^{-1}$ by the end of the season. The photoperiod declined from 12:24 hours to 10:27 at the end of the season. This suggest that plants grown under these condition could inhibit vegetative and reproductive shoot growth.

Conclusion

Field-grown dahlias appear to have market quality issues with stem length, as well as lower stem yields when compared to the high tunnel. Stem lengths in the field were subject to significant yearly climate variation which increases risk when producing in the NGP. ‘Irene’ produced more harvestable stems in most environments as well as more stems overall when transplanted at either soil temperature. This suggests that for field plantings ‘Irene’ was more desirable.

Dahlias are best suited for production in the high tunnel for the NGP. High tunnels experienced a longer growing season, with increased ADT and GDU as well as similar DIF and DLI when compared to the field. Total stems harvested increased; as well as stem lengths and calipers compared to the field; however, the high tunnel has the potential to produce unmarketable stem lengths. That risk can be reduced though, by carefully managing night temperatures through ventilation to ensure a positive DIF. Soil transplanting temperature in the high tunnel influenced stem calipers, producing increased calipers when transplanting was delayed, however both soil transplanting temperatures resulted in stem caliper greater than market quality standards, suggesting less of a concern about transplanting timing with regards to the high tunnel. Cultivar differences were not observed within the high tunnel for total stems and stem length, but differences were observed for caliper. However, as with soil transplanting temperature, cultivar differences were not a concern since both were in excess of quality standards.

CHAPTER II. EVALUATION OF HIGH TUNNEL AND FIELD GROWN SNAPDRAGON AS A SPECIALTY CUT FLOWER IN THE NORTHERN GREAT PLAINS

Introduction

Antirrhinum majus L. (snapdragon) is an herbaceous perennial that is grown commercially both as a bedding plant and as a cut flower. There has been a resurgence of interest in snapdragon production in high tunnel and field systems (Armitage and Laushman, 2003). Commercial snapdragon cultivars are typically produced from seeds and have flowers on tall racemes. Flowers are commonly 3.5 to 4.5 cm long, zygomorphic, and are available in a wide range of colors (Shiva and Singh, 2006). As a major cut flower crop, snapdragon is commonly sold in bunches of 10 floral stems with a wholesale market value currently ranging from \$12.50 to \$13.50 per bunch (USDA, 2019). The average vase life of a raceme is seven days, but with the addition of a floral preservative, such as silver-thiosulfate, and daily water changes, this can be extended to approximately 21 days (Ichimura and Hismatsu, 1999). Snapdragon is very sensitive to ethylene exposure, which when allowed to fall off the raceme; i.e. shatter, thus destroying the value of the floral shoots (Heffron, 2006). This sensitivity makes snapdragon a candidate for domestic production rather than for shipping from foreign countries.

Morphology

Many cultivars are quantitative long-day plants; they will flower under short days but will flower faster under long days (Cremer et al., 1998; Runger and Cockshull, 1985). Several studies have identified average daily temperature (ADT) and daily light integral (DLI) for controlling growth rate and development in snapdragon cultivars, if growth inputs are not limited (Blanchard and Runkle, 2004.; Pramuk and Runkle, 2005; Warner and Erwin, 2005). As the DLI increased from 10 to 20 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ at a ADT of 20°C, flower bud number increased by 63% in snapdragon

(Warner and Erwin, 2005b). Decreasing the DLI from 21.8 to 10.5 $mol \cdot m^{-2} \cdot d^{-1}$at 32°C reduced dry mass rates as well as delayed flowering (Pramuk and Runkle, 2005). Additionally, temperature and DLI influence plant quality characteristics, including flower number and size, branch number, plant height, and plant biomass (Neily et al., 1997; Vaid et al., 2014; Wai and Newman, 2019).

Scientific research into production of snapdragon in the field and high tunnel is limited. Ortiz et al. (2012) reported that the cultivar Rocket Red yielded more stems in the high tunnel than in the field. Compared with field production, high tunnel production yielded 16% more stems with 33% longer stem length. No differences were observed for average stem caliper in the field and high tunnel. In the same study, the cultivar Potomac Orange produced 10.4 cm longer stems in the high tunnel, but stem caliper was 0.51 mm smaller than field-grown stems. The average number of stems were similar in the field and high tunnel. In 2014 Zhao et al., reported on the effect of planting date on ’Potomac Red’ in high tunnels. Planting dates (12 March, 2 April) did not influence total yield (11 to 58 stems m^{-2}). Sherrer evaluated multiple snapdragon cultivars grown in four plastic mulches (red, white, blue, and black), and bare ground in a high tunnel production system (2010). Effects were cultivar specific, but most cultivars produced the longest stems on black, red, and white mulch. Black and blue plastic mulch produced the thickest stems.

Limited research combined with postharvest storage problems such as poor vase life after cold storage (Çelikel et al., 2010), gravitropic stem bending when flowers are handled or stored horizontally (Philosoph-Hadas,et al., 1996), and ethylene sensitivity make it difficult to import and distribute snapdragon in the US. Snapdragon cultivars should be evaluated for production in all regions of the US, including the Northern Great Plains (NGP), to ensure the competitiveness of domestic specialty cut flowers. Therefore, the objective of this study was to evaluate two snapdragon cultivars transplanted under two soil temperatures in the high tunnel and field at two NGP locations.

Materials and Methods

Two independent but identical field and high tunnel experiments were carried out at two locations in North Dakota (that approximate two distinct east and west regions in the NGP) during the years 2016 and 2017. The eastern location was located at the Dale E. Herman Research Arboretum near Absaraka, ND (46°59'27.9" N and 97°21'20.1" W ("Absaraka")). The western location was at the Williston Research Extension Center's Nesson Valley Irrigation Research Site near Williston, ND (48°09'46.3" N and 103°06'29.4" W ("Williston"). The two cultivars Potomac White and Rocket Mix ('PW' and 'RM'), and two transplanting soil temperatures (13 °C and 18 °C) were used in each experiment (Germania Seed Company, Chicago, IL, USA). On 14 April 2016 and 21 April 2017, respectively, rooted cuttings were received and transplanted within 7 days into 606-deep cell packs (205 mL individual cell volume; T.O. Plastics, Clearwater, MN, USA) using a commercial soilless medium (PRO-MIX BX Mycorrhizae; Premier Tech Horticulture, NB, CA). Plant material was maintained at a day/night (D/N) temperature 21±3 °C /18±3 °C with forced-air heating. Supplemental lighting was provided by a high-pressure sodium lamp (GE Ecolux-1000, GE Lighting Solutions LLC, Cleveland, OH ,USA) on a 12-hour D/N cycle, controlled by an environmental control system (Maximizer Precision 10; Priva Computers, Vineland Station, ON, CA) in a glass-glazed greenhouse at North Dakota State University in Fargo, ND.

High Tunnel and Field Environments

Plants were transplanted based on daytime average soil temperatures at a depth of 15 cm of either 13 or 18 °C, in their respective production environments (Table 1). In 2016, the transplanting dates ranged from 20 May to 10 June. Planting dates in 2017 began on 24 April and continued until 2 June. Both high tunnels (30 m long, 9 m wide, 5 m tall) were constructed with a triple-galvanized structural steel frame and were covered with 6 mm exterior polyethylene film and a 4-mm polyethylene interior film with tri-layer construction and ultraviolet additives that allowed 90% light transmission (Rimol Greenhouse Systems, Hooksett, NH, USA). Activated by temperatures, automated end-wall peak vents (21.1 °C) and roll-up sidewalls (26.6 °C) provided most of the ventilation. Two large garage doors located on both end walls provided additional ventilation when needed. The sidewalls were raised during periods of high winds. The soil for the Absaraka experiments is from the Warsing series (fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Oxyaquic Hapludolls) containing 1.2% organic matter and a pH of 7.2. The soil for the Williston experiments is from the Bowdle series (fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Pachic Haplustolls) with 2.1% organic matter and a pH of 7.0. A total of ten beds (13.7 m long ·1 m wide) at each site were constructed in a north-south orientation, five in the field and five in the high tunnel. All 10 beds were broadcast fertilized using 20-10-20 with micronutrients (JR Peters Inc., Allentown, PA, USA) at a rate of 84 kg·ha-1. A 0.4 mm thick drip watering system with 20.3 cm emitter spacing and 4.5 x 10-5 m3·s-1 flow rate was installed in each plot (Aqua-Traxx; The Toro Company, Bloomington, MN, USA). Each plot with two plant rows had three individual lines to provide water effectively and efficiently. Each sub-plot was run on an individual timer and solenoid valve to optimize water usage.

Data Collection

Resistance-based temperature sensors (External Temperature Sensor; Spectrum Technologies, Inc., Plainfield, IL, USA), enclosed thermocouples, and conductivity sensors (GS3 Soil Moisture, Temperature and Electrical Conductivity Sensor, Meter Group, Inc. Pullman, WA, USA) recorded soil and air temperature and soil water volume respectively, every 30 s and averages were calculated every 5 min by a data logger (Watch Dog Model 2475-Plant Growth

Station; Spectrum Technologies, Inc, Aurora, IL, USA). Each whole plot received its own data logger with five sensors spaced out evenly in a circular pattern from the center. Each sensor chosen was tested then calibrated to reduce variation. All daily light integral (DLI) measurements were plotted for each environment from data collected at the North Dakota Agriculture Weather Network stations near the respective sites. Growing degree units (GDU) were calculated from air temperature data collected and calculated using base 13°C (average daily temperature °C (ADT) - 13°C) where ADT (°C) = (maximum daily temp °C (MAX) + minimum daily temp °C (MIN)) (Romo and Eddleman, 1995). average daily temperature, MAX, MIN, and day/night differential (DIF) were derived from temperature data collected in their respective environments. Morphological data collected included flower number, stem length, and stem caliper from stems harvested twice a week. Stem marketability was determined by length (greater than 30 cm), caliper (greater than 4 mm) and flower quality (no visual damage) (Barr, 1992).

Experimental Design and Statistical Analysis

Each experiment was laid out in a randomized complete block design with a split-split plot in time arrangement. Each experiment investigated environmental (location by year) differences (whole plot factor A), two cultivars (factor B sub-plot), and two soil transplanting temperatures (factor C sub-sub-plot). Environments were represented by year (2016 or 2017) and location (A for Absaraka and W for Williston). Each experimental unit was 1 m x 0.5 m and contained eight plants spaced 20 cm apart with a total area of 0.5 m2 with four replications. Average number of stems will be reported on a square meter basis. Data was analyzed with SAS (SAS 9.4, SAS Institute, Cary, NC) General Linear Mixed Model (PROC GLMM) using the Auto-Recursive 1 structure.

Results

Average Number of Stems Per Square Meter

Results were analyzed separately for high tunnel and field production. The main effects of environment (factor A) and cultivar (factor B) were significant for average number of stems in the high tunnel. In the field, the interactions between cultivar by environment and temperature by cultivar were significant for number of stems harvested (Appendix A6). Fewer stems were harvested from plants in the high tunnel in the 2016 Williston environment (16W) when compared to the three other environments (Figure 7). High tunnel plants in the Absaraka environments in 2016 (16A) and 2017 (17A) and the Williston environment in 2017 (17W) produced similar numbers of stems ranging from 218 to 311 stems. The cultivar RM yielded more stems than 'PW' in the high tunnel, with an average of 280 stems, an increase of ~40% over 'PW' (202 stems) (Data not shown).

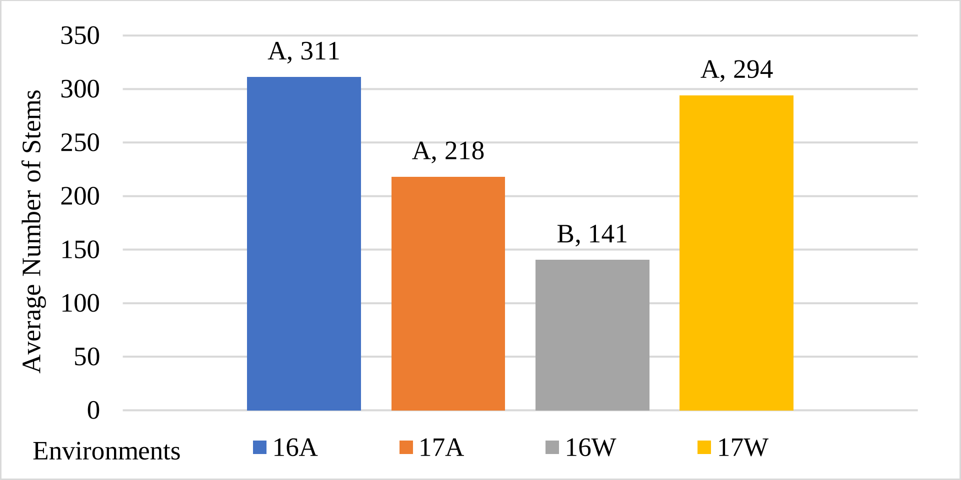

Figure 7. Main Effect of Environment (Location by Year) on Average Number of Snapdragon Stems per Square Meter Harvested in the High Tunnel. Mean totals with a common letter are not different ($P \leq 0.05$) by Tukeys HSD test (n= 3). Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston.

In the field, 'RM' produced significantly more stems on average than 'PW' in the 2016 and 2017 Williston environments ranging from 166 to 173stems (Figure 8). In these two environments, the average number of ‘PW’ stems were only 52 to 70. No significant differences occurred between cultivars in the two Absaraka environments.

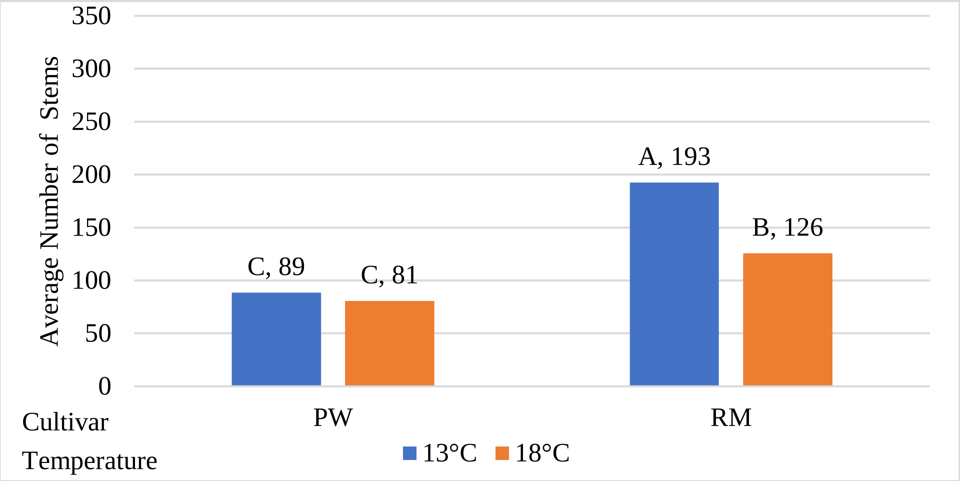

Figure 8. Interaction of Cultivar and Environment (Location by Year) on Average Number of Snapdragon Stems per Square Meter Harvested in the Field. Mean totals with a common letter are not different ($P \leq 0.05$) by Tukeys HSD test. n= 3. Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston ‘PW’ = Potomac White ‘RM’ = Rocket Mix.

The cultivar PW did not respond to different soil transplanting temperatures in the field as plants transplanted at either 13 °C or 18 °C bore similar numbers of stems (81 to 89) (Figure 9). Delayed transplanting of ‘RM’ at 18 °C resulted in a 33% decrease in number of stems harvested. Regardless of soil transplanting temperature, more stems were harvested from ‘RM’ plants (193 stems) compared to ‘PW’ (126 stems).

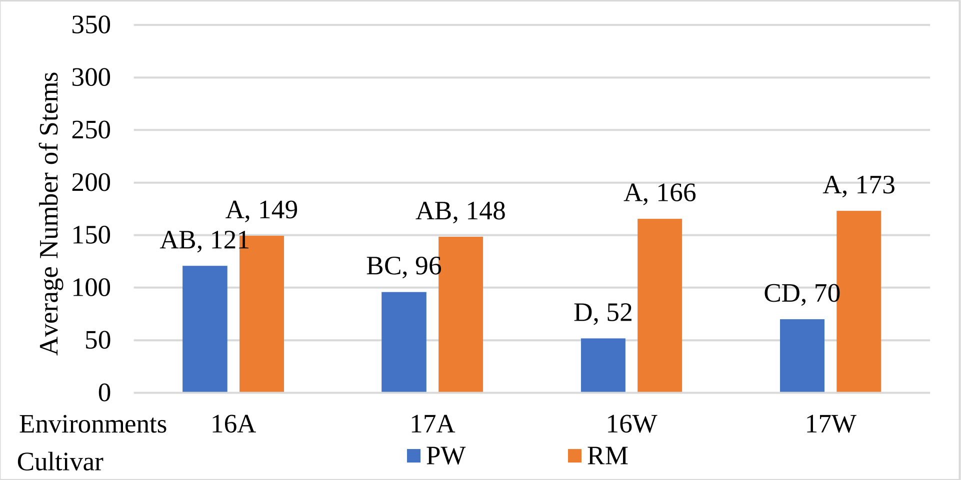

Figure 9. Interaction of Cultivar and Temperature on Average Number of Snapdragon Stems per Square Meter Harvested in the Field. Mean totals with a common letter are not different ($P \leq 0.05$) by Tukeys HSD test (n= 2). Abbreviations: ‘PW’ = Potomac White, ‘RM’ = Rocket Mix.

Stem Length

The main effects of environment and cultivar were significant for average stem lengths in the high tunnel. Conversely, no main effects or interactions were significant for average stem lengths in the field (Appendix A6). In the high tunnel, plants in 2017 Absaraka and 2016 Williston, produced stems with average lengths of 47 to 50 cm, significantly longer stems than those produced by plants in 2017 Williston (33 cm) (Figure 10). Plants in 2016 Absaraka produced stems with an average length of 42 cm, which was similar to 2016 Williston. Plants in 2017 Williston produced the shortest stems averaging 33 cm. ‘PW’ produced longer stems on average (45 cm) compared to ‘RM’ (41 cm) (Data not shown).

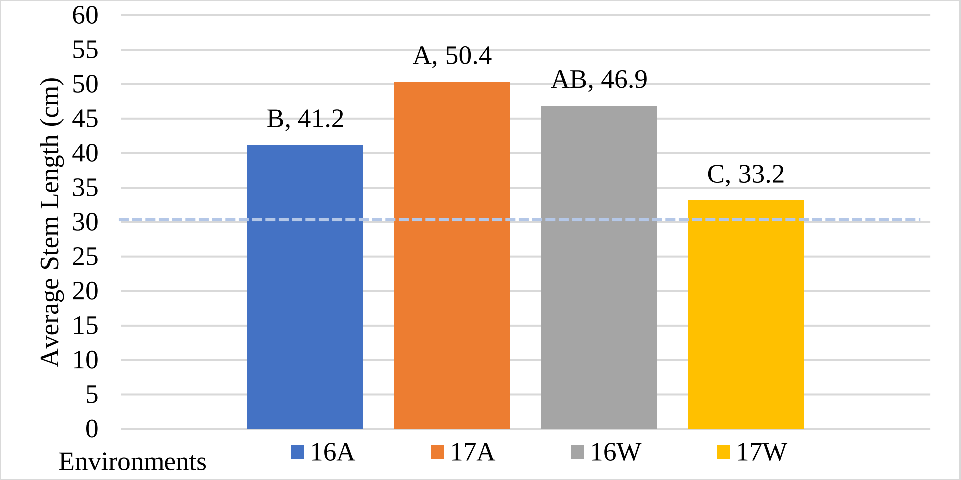

Figure 10. Main Effect of Environment (Location by Year) on Snapdragon Stem Lengths Harvested in the High Tunnel. Mean totals with a common letter are not different ($P \leq 0.05$) under Tukeys HSD test (n= 3). Blue dashed line represents minimum length to be considered marketable (30 cm) Barr, 1992. Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston.

All plants, regardless of the environment or cultivar, produced stems above the minimum marketable length of 30 cm in the high tunnel. The overall average stem length in the field was 30.4 cm, well above the minimum market standard (data not shown).

Stem Caliper

Two interactions between environment by cultivar as well as temperature (factor C) by cultivar were significant for average stem caliper in the high tunnel. No main effects or interactions were significant for average stem calipers in the field (Appendix A6). Both cultivars, RM and PW in 2016 Absaraka, had stems with greater caliper than other environments, ranging from an average of 8.3 to 8.8 mm (Figure 11). Stem calipers for ‘RM’ and ‘PW’ plants in the 2017 Absaraka environment decreased significantly (nearly 50%) compared to 2016, but were still above market standards of 4 mm. In Williston, each cultivar and year combination was unique. In 2016, ‘PW’ plants produced stems with an average caliper of 6.5 mm, 25% greater than ‘RM’ stem caliper (5.0 mm). Both cultivars produced stems with marketable stem caliper in 2016 Williston. In 2017 Williston, neither cultivar produced stems that met the market standard. In 2017 Williston, ‘RM’ averaged stems with a caliper of 3.8 mm, a 44% increase over ‘PW’ plant stem caliper (2.1 mm).

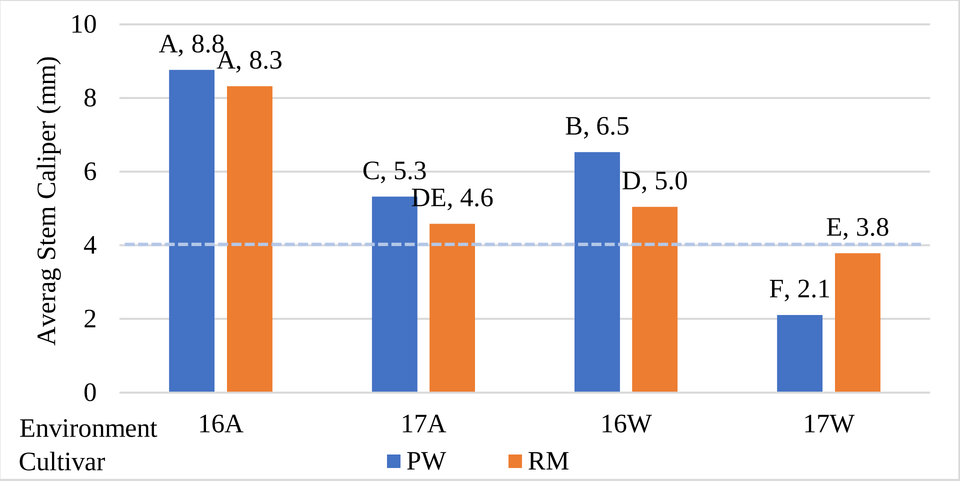

Figure 11. Interaction of Environment (Location by Year) and Cultivar on Average Snapdragon Stem Calipers Harvested in the High Tunnel. Mean totals with a common letter are not different ($P \leq 0.05$) by Tukeys HSD test (n= 3). Blue dashed line represents minimum length to be considered marketable (4 mm) Barr, 1992. Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston ‘PW’ = Potomac White, ‘RM’ = Rocket Mix.

The interaction of environment and soil transplanting temperature on average snapdragon stem calipers harvested in the high tunnel was significant; however, no significant differences emerged between soil transplanting temperatures in any environment (Figure 12). Yearly environmental variation was observed with 2017 plants having greatly reduced average stem caliper compared to 2016 plants in both locations, regardless of the soil transplanting temperature. All environments except 2017 Williston yielded average stem calipers that exceeded the minimum market standards.

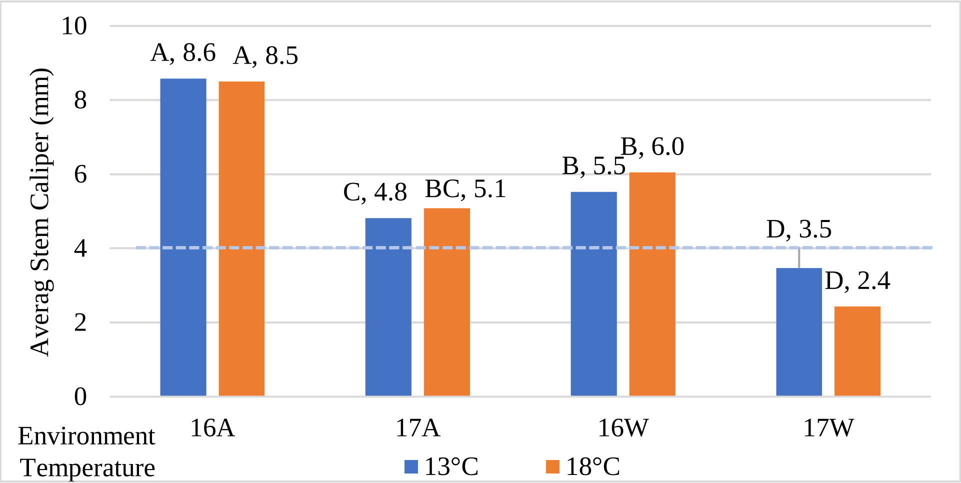

Figure 12. Interaction of Environment (Location by Year) and Soil Transplanting Temperature on Average Snapdragon Stem Calipers Harvested in the High Tunnel. Mean totals with a common letter are not different ($P \leq 0.05$) under Tukeys HSD test. n= 3. Blue dashed line represents minimum length to be considered marketable (4 mm) Barr, 1992. Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston

No main effects or interactions were significant for average stem caliper of snapdragons grown in the field (Appendix A6). The overall average stem caliper was 4.2 mm, above marketable standards (data not shown).

Discussion

High Tunnel

The high tunnel environment can be beneficial for snapdragon production. Its sheltered environment can overcome many of the climatic difficulties in the NGP region. Three of the four environments were statistically similar with average number of stems ranging from 218 to 311 stems per square meter. Williston in 2016 was the exception with approximately 50% fewer stems produced on average (140 stems). No causal connection could be found for the lower production in 2016 Williston when examining various environmental factors including GDU (Appendix B2), ADT and DLI (Appendix A2), MAX, MIN, DIF (Appendix A3). Average daily temperature was similar for all environments ranging 23.9 °C to 25.7 °C from May to August with an incremental decline from September to November. MAX and MIN temperatures were similar from May to October, with the notable exception of April 2016 associated with high tunnel construction.

Cultivar differences emerged as well for average number of stems grown in the high tunnel, with ‘RM’ producing an average of 280 stems a 40% increase over ‘PW’ 200 stems. A similar experiment conducted by Ortiz et al. (2012) reported that stems harvested for the snapdragon cultivar Rocket Red was 183 stems, a 900% increase compared to the snapdragon cultivar Potomac Orange (20 stems m-2) when grown in the high tunnel. Our results in the current study agree with the previous research albeit to a lesser magnitude. Differences in production are most likely attributed to cultivar variation within series and yearly climatic variation. Average snapdragon stem length in the high tunnel was influenced by environmental and cultivar differences. Plants in 2017 Williston produced shorter stems on average compared to plants in the other environments even though all environments were within marketable standards. ‘PW’ averaged 9% longer stems compared to ‘RM’. These results also agreed with Ortiz et al. (2012) findings, which reported longer lengths for ‘Potomac Orange’ (82.2 cm) in the high tunnel a 36 % increase over ‘Rocket Red’ (51.8 cm).

When examining flower stem caliper, two interactions, environment by cultivar and environment by temperature, influenced stem caliper for snapdragons grown in the high tunnel. Cultivar differences emerged only at the Willison location. ‘PW’ in 2016 Williston had a greater average stem caliper when compared to ‘PW’ plants in 2017 Williston. This suggests that yearly variation in plant materials may contribute the variation in snapdragon stem calipers. Examination of environment by temperature influence on stem caliper indicated that no differences emerged for transplanting temperature and that yearly climatic variation emerged as the primary source of significance. In 2017 Williston, stem calipers were below marketable quality for both cultivars and transplanting temperatures respectively, as well as reduced stem length comparatively. When examining ADT and MAX, we see that 17W experienced a mean temperature of 29.6 °C and a mean maximum temperature of 46.1 °C during the month of July, a 11.4% and 5.6% increase respectively compared to the other environments (Appendix A2, A3). This suggests a connection between elevated temperatures and the potential for reduced length and calipers in the high tunnel.

Examining average daily soil temperature for the 2017 Williston environment we see during late summer (June to August) average soil temperature within the 15 cm of the surface was between 28.5 to 32.7°C (Appendix A2). This is consistent with previous research that found snapdragons with the root zone at 30°C had shorter stems and a lower dry weight than those at 20°C (Wai and Newman, 2019). Hood and Mills, (1994) report. Optimal temperatures for nutrient uptake and growth were similar for various cultivars, averaging 22°C. These results indicate increasing or maintaining root-zone temperatures near 22°C maximizes growth and nutrient uptake of snapdragons. Examining air and soil temps observed within the high tunnel we see that the general trends were identical between air and soil temperature which is consistent with studies showing close relationships between air and soil temperature (Parton and Logan, 1981; Zheng et al., 1993). In April ADT and average soil temp were initially 22 to 23°C, near optimum levels for growth and nutrient uptake. Increasing gradually until their maximum in July of 27 to 32°C, well out of the ideal range, and then declining below 20°C shortly after September.

Field

In the field, the interactions of cultivar by environment and cultivar by temperature influenced snapdragon stem production. 'PW' showed no response to soil transplanting temperature; however, it did show a response to environment. Stems harvested at Absaraka averaged 108 stems while plants at Williston averaged 60 stems. Ortiz et al. (2012) reported stems densities for 'Potomac Orange' of 18 stems m^{-2}. Zhao et al. (2014) investigated planting date on yield of field grown snapdragons in Mississippi and reported that ‘Potomac Red’ produced between 20 to 24 stems m^{-2}. In 2016, a preliminary report, found that ‘Potomac Lavender’ produced 4.4 to 7.0 stems(Owen et al., 2016.) These studies all show that the Potomac series produces a relatively low number of stems m^{-2}. Stem densities produced in the current research project were greater for both locations compared to previous published studies, suggesting that the NGP has the potential to produce greater snapdragon yields for the Potomac series than other regions. This is in alignment with research that indicates snapdragons can tolerate and even prefers cooler growing temperatures (Itol et al., 1997)(Semeniuk and Stewart, 1960; Wai and Newman, 2019).

The cultivar RM showed no response to environment; however, it did show a response to soil transplanting temperature. Average number of stems harvested for ‘RM’ was between 148 to 174, over all environments. Ortiz et al. (2012) reported that production for ‘Rocket Red’ was 153 stems m^{-2}. Our results were consistent with the previous work suggesting that the NGP should be suitable for field production of the Rocket series. Fewer stems were harvested when transplanting was delayed from 13°C to 18°C for ‘RM’; however, ‘RM’ under both transplanting temperatures still yielded more stems compared to ‘PW’. This result is also in agreement with Ortiz et al. (2012) finding greater production in general for the Rocket series compared to the Potomac series. This suggests that for field growth, ‘RM’ is more adaptable to early spring climatic variations compared to ‘PW’ and can take advantage of cooler soils in the spring.

Snapdragon stem lengths and caliper showed little variability, averaging marketable lengths and calipers (30.4 cm, 4.2 mm) over all environments, cultivars, and transplanting soil temperatures. This contrasts with Ortiz et al. (2012) findings, which reported longer lengths for ‘Potomac Orange’ (71.8 cm) in the field, a nearly two-fold increase over ‘Rocket Red’ (39.0 cm) as well as greater stem calipers for ‘Potomac Orange’ (9.2 cm) over ‘Rocket Red’ (6.0 cm). Wien (2009) reported snapdragon stem lengths of 54 to 60 cm when grown in the field. This suggests that a tradeoff occurs in NGP field production and that more stems may result in shorter stem length and smaller calipers compared to other regions of the US.

Conclusion

Production of cut flower snapdragons in the field is feasible throughout the NGP. Snapdragons stems showed no significant variation in stem length and caliper, each averaging on the low end of what was considered marketable. Total stem production was reduced when compared to the high tunnel; however, production was equivalent or greater than similar field production carried out in other regions of the US. Cultivar differences emerged by location. ‘PW’ yielded significantly more stems in Absaraka than in Williston in both years. ‘RM’ produced uniform’ results regardless of location or year. More stems were also harvested from ‘RM’ regardless of the transplanting soil temperature, suggesting that for field plantings ‘RM’ was more adaptable in the NGP.

The high tunnel appears to be better suited for production of higher quality snapdragons, producing more average stems when anecdotally compared to the field, as well as increased production compared to similar experiments carried out in high tunnels in the Midwest. Stem length showed variation by environment; however, average stem length was well above market standards and exceeded results in the field. Cultivar differences also emerged in the high tunnel for stem length with ‘PW’ producing on average 9% longer stems than ‘RM’. Calipers were subject to yearly trends and variation within environment as well as cultivar. Stem calipers were greater in 2016 across all locations, temperatures, and cultivars compared to 2017. Three out of the four environments produced calipers in excess of marketable standards, with 17W producing less than marketable stem calipers. This was likely caused by excessive heat units which could be potentially mitigated by shading. Cultivar differences emerged, but were mixed, each cultivar preformed similar in Absaraka, but diverged in Williston with ‘PW’ having greater calipers in 2016 and ‘RM’ in 2017. No clear preference for either cultivar emerged in the high tunnel.

CHAPTER III. EVALUATION OF HIGH TUNNEL AND FIELD GROWN LISIANTHUS AS A SPECIALTY CUT FLOWER IN THE NORTHERN GREAT PLAINS

Introduction

Eustoma grandiflorum **(**lisianthus) is an herbaceous annual, growing 15 to 60 cm tall, with bluish-green, waxy leaves. It develops large funnel-shaped flowers growing on either erect single stems or on branching stems that can rise to be 1.5 m in length (Armitage and Laushman, 2003). The flowers can grow up to 5 cm in width and are available in a variety of colors, including pink, purple, white, and blue. In addition, lisianthus flowers can be single-flowered or double-flowered depending on cultivar (Dole and Wilkins, 1999).

Morphology

Two main growth phases have been identified for lisianthus, seedling and bolting stage (Armitage and Laushman, 2003). During the seedling stage (fewer than five leaf pairs), short days (<12 h) and temperatures between 7 to 18 °C are desirable to enhance vegetative growth to support proper flower development and maturation (Roh et al., 1989; Armitage and Laushman, 2003). During the stem elongation (bolting) stage, which includes floral initiation and development, long days (>12 h) and temperatures between 15 and 25 °C are desirable to enhance floral development (Armitage and Laushman, 2003; Harbaugh et al., 1992). Temperatures above 21 °C at the seedling stage and 25 °C during bolting stage, can result in rosetting of the plants (Harbaugh et al., 1992). Rosetting is defined as the failure to produce a flowering stem within an acceptable cropping period (≈140 days). If rosetting occurs, in addition to plants not producing flower stems, stems that are produced will generally be lower quality (Armitage and Laushman, 2003).

Research examining lisianthus production in the field and high tunnel is limited. Ortiz et al. (2012) reported that total harvested stems were similar in the high tunnel and field (89 to 90 stems m-2). Stems harvested from the high tunnel were, on average, 15 cm longer than field-grown with no differences in stem caliper. An evaluation of 47 lisianthus cultivars as field-grown cut flowers reported a wide range of variance in vegetative and flowering attributes (Harbaugh et al., 2000). International growers also tend to avoid this challenging crop due to its low germination percentages, slow growth, and short postharvest vase life (Nau, 2011). Senescence of cut flowers is induced by water stress (Sankat and Mujaffar, 1998), carbohydrate depletion (Ketsa, 1989), microorganisms (Witte and van Doorn, 1991), and ethylene sensitivity(Wu et al., 1991; Farokhzad et al., 2005), all of which generally result in the need for short distance transport and storage, and make lisianthus an ideal choice for local, high-value crop production. The objective of this study was to evaluate three lisianthus cultivars under field and high tunnel production methods in the Northern Great Plains (NGP). Lisianthus cultivars should be evaluated further for all regions of the US, including the NGP, to ensure the competitiveness of domestic specialty cut flowers.

Materials and Methods

Two independent but identical field and high tunnel experiments were conducted at two east and west locations in North Dakota. The eastern location was located at the Dale E. Herman Research Arboretum near Absaraka, ND (46°59'27.9" N and 97°21'20.1" W (“Absaraka”)). The western location was at the Williston Research Extension Center’s Nesson Valley Irrigation Research Site near Williston, ND (48°09'46.3" N and 103°06'29.4" W (“Williston”). Three cultivars (Mariachi Misty Blue, Echo Blue and ‘ABC’ 2), represented by the abbreviations ‘MMB’, ‘EB’, and ‘ABC’ [Germania Seed Company, Chicago, IL, USA]), and two soil transplanting temperatures (13 °C and 18 °C) were used in each experiment. On 14 April 2016 and 21 April 2017, respectively, rooted cuttings were received and transplanted within 7 days into 606-deep cell packs (205 mL individual cell volume; T.O. Plastics, Clearwater, MN, USA) using commercial soilless medium (PRO-MIX BX Mycorrhizae; Premier Tech Horticulture, NB, CA).

Plant material was maintained at a day/night (D/N) temperature 21±3 °C /18±3 °C with forced-air heating. Supplemental lighting was provided by a high-pressure sodium lamp (GE Lucalox 1000, GE Lighting Solutions LLC, Cleveland, OH, US) on a 12-hour D/N cycle, controlled by an environmental control system (Maximizer Precision 10; Priva Computers, Vineland Station, ON, CA) in a glass-glazed greenhouse at North Dakota State University in Fargo, ND.

High Tunnel and Field Environments

Plants were transplanted based on daytime average soil temperatures at a depth of 15 cm of either 13 or 18 °C, in their respective production environments (Table 1). In 2016, the transplanting dates ranged from 20 May to 10 June. Planting dates in 2017 began on 24 April and continued until 2 June. Both high tunnels (30 m long, 9 m wide, 5 m tall) were constructed with a triple-galvanized structural steel frame and were covered with 6-mm exterior polyethylene film and a 4-mm polyethylene interior film with tri-layer construction and ultraviolet additives that allowed 90% light transmission (Rimol Greenhouse Systems, Hooksett, NH, USA). Activated by temperatures, automated end-wall peak vents (21.1 °C) and roll-up sidewalls (26.6 °C) provided most of the ventilation. Two large garage doors located on both end walls provided additional ventilation when needed. The sidewalls were raised during periods of high winds. The soil for the Absaraka experiments is from the Warsing series (fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Oxyaquic Hapludolls) containing 1.2% organic matter and a pH of 7.2. The soil for the Williston experiments is from the Bowdle series (fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Pachic Haplustolls) with 2.1% organic matter and a pH of 7.0. A total of ten beds (13.7 m long ·1 m wide) at each site were constructed in a north-south orientation, five in the field and five in the high tunnel. All 10 beds were broadcast fertilized using 20-10-20 with micronutrients (JR Peters Inc., Allentown, PA, USA) at a rate of 84 kg·ha-1. A 0.4 mm thick drip tape watering system with 20.3 cm emitter spacing and 4.5 x 10-5 m3·s-1 flow rate was installed in each plot (Aqua-Traxx; The Toro Company, Bloomington, MN, USA). Each plot with two plant rows had three individual lines to provide water effectively and efficiently. Each sub-plot was run on an individual timer and solenoid valve to optimize water usage.

Data Collection

Resistance-based temperature sensors (External Temperature Sensor; Spectrum Technologies, Inc., Plainfield, IL, USA), enclosed thermocouples, and conductivity sensors (GS3 Soil Moisture, Temperature and Electrical Conductivity Sensor, Meter Group, Inc. Pullman, WA, USA) recorded soil and air temperature and soil water volume respectively, every 30 s and averages were calculated every 5 min by a data logger (Watch Dog Model 2475-Plant Growth Station; Spectrum Technologies, Inc, Aurora, IL, USA). Each whole plot received its own data logger with five sensors spaced out evenly in a circular pattern from the center. Each sensor chosen was tested then calibrated to reduce variation. All daily light integral (DLI) measurements were plotted for each environment from data collected at the North Dakota Agriculture Weather Network (NDAWN) stations near the respective sites. Growing degree units (GDU) were calculated from air temperature data collected and calculated using base 13 °C (average daily temperature °C (ADT) – 13 °C) where ADT (°C) = (maximum daily temp °C (MAX) + minimum Daily Temp °C (MIN)) (Romo and Eddleman, 1995). average daily temperature, MAX, MIN, and day/night differential (DIF) were derived from temperature data collected in their respective environments. Morphological data collected included flower number, stem length, and stem caliper from stems harvested twice a week. Stem marketability was determined by length (greater than 30 cm), caliper (greater than 4 mm) and flower quality (no visual damage) (Barr, 1992).

Experimental Design and Statistical Analysis

Each experiment was laid out in a randomized complete block design (RCBD) with a split-split plot in time arrangement. Each experiment investigated environmental (location and year) differences (whole plot factor A), two cultivars (factor B sub-plot), and two soil transplanting temperatures (factor C sub-sub-plot). Environments were represented by year (2016 or 2017) and location (A for Absaraka and W for Williston). Each experimental unit was 1 m x 0.5 m and contained eight plants spaced 20 cm apart with a total area of 0.5 m2 with four replications. Average total stem data will be displayed on a square meter basis. Data was analyzed with SAS (SAS 9.4, SAS Institute, Cary, NC) General Linear Mixed Model (PROC GLMM) using the Auto-Recursive 1 structure.

Results

Average Number of Stems Per Square Meter

In the high tunnel, only the interaction of environment by temperature was significant, for average number of stems. In the field, the main effect of soil transplanting temperature was significant as well as the interaction between cultivar and environment (Appendix A7). In 2016, soil transplanting temperatures did not affect the average number of stems harvested; however, the environment had a significant effect (Figure 13). In 2016 Williston, an average of 68 to 75 stems were harvested, while approximately 140 stems were harvested in the 2016 Absaraka high tunnel. In contrast, the effect of soil transplanting temperature was significant in 2017. In 2017 Absaraka, when transplanting was delayed until the soil warmed to 18 °C, the average number of stems decreased from 120 (13 °C) to 83 (18 °C). In Williston, a similar trend was observed when transplanting was delayed, with average number of stems decreasing from 217 stems (13 °C) to 146 stems (18 °C).

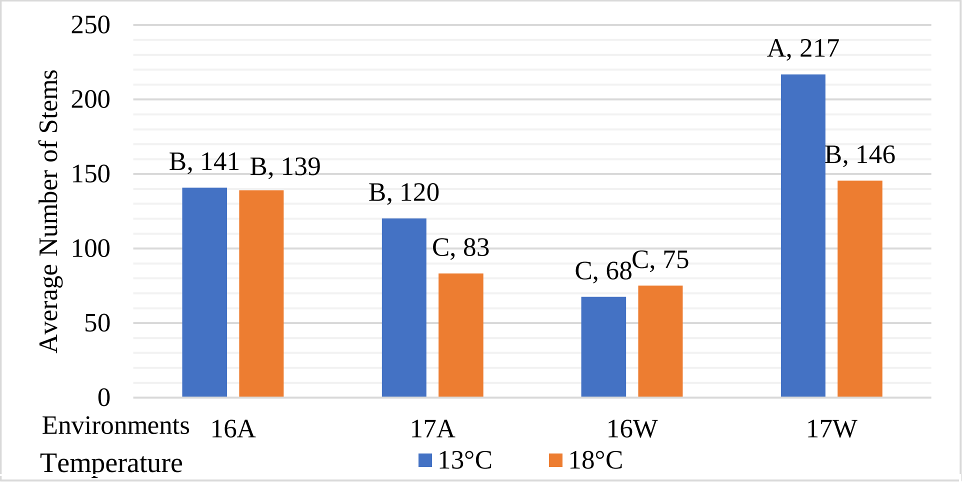

Figure 13. Interaction of Environment (Location by Year) and Soil Transplanting Temperature on Average Number of Lisianthus Stems Harvested per Square Meter in the High Tunnel. Mean totals with a common letter are not different ($P \leq 0.05$) by Tukeys HSD test (n= 3). Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston.

Average number of stems harvested in the field were cultivar and environment specific. In 2016 Williston, 'MMB' had the largest number of stems harvested (102), an increase compared to the other cultivars in the same environment (47 to 59 stems) (Figure 14). In 2017 Williston, no significant cultivar differences emerged, and average number of stems ranged from 78 to 99 stems; however, when compared to 2016 Williston the production for 'MMB' decreased 23%, while 'EB' increased by 100%, and 'ABC' had similar stems harvested. No significant environmental or cultivar differences emerged in the Absaraka location with average number of stems harvested ranging from 47 to 70 stems for both years. In the field, when transplanting was delayed until the soil warmed to 18 °C, the average number of stems decreased from 60 stems (13 °C) to 52 stems (18 °C) (Data not shown).

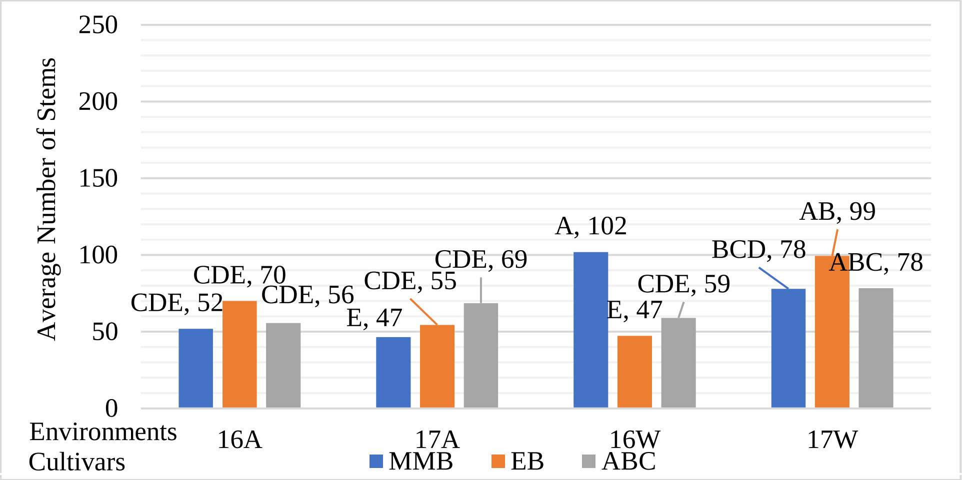

Figure 14. Interaction of Environment (Location by Year) and Cultivar on Average Number of Lisianthus Stems Harvested per Square Meter in the Field. Mean totals with a common letter are not different ($P \leq 0.05$) by Tukeys HSD test (n= 6). Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston, 'MMB' = Mariachi Misty Blue, 'EB' = Echo Blue and 'ABC' = 'ABC' 2 Blue.

Stem Length

The two-way interaction of environment by cultivar was significant for average stem length in both high tunnel and field production systems (Appendix A7). In the high tunnel, the longest average stem lengths were observed for 'MMB' in Absaraka for both years with lengths ranging from 42.1 to 44.7 cm (Figure 15). In 2016 and 2017 Williston, stem lengths for 'MMB' were shorter than the Absaraka environments by 11% with lengths ranging from 38.1 to 38.6 cm. Stem lengths for 'EB' were similar over all environments ranging from 34.5 to 36.8 cm. For cultivar 'ABC', the longest average stem length was observed in 2016 Absaraka (33.5 cm). The remaining environments had similar stem lengths that were below market quality standards (30 cm) ranging from 27.4 to 28.8 cm, a significant decrease from all other cultivar by environmental combinations.

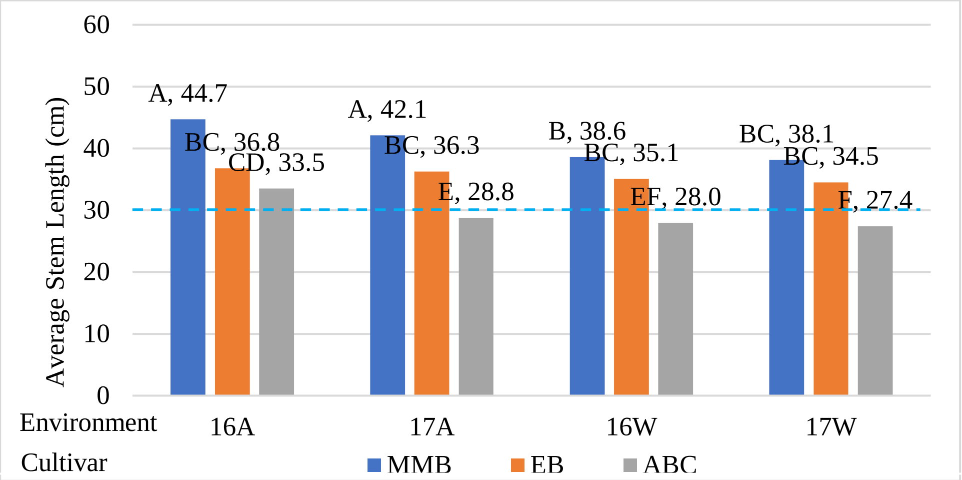

Figure 15. Interaction of Environment (Location by Year) and Cultivar on Average Lisianthus Stem Length Harvested in the High Tunnel. Mean totals with a common letter are not different ($P \leq 0.05$) by Tukeys HSD test (n= 6). Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston, ‘MMB’ = Mariachi Misty Blue, ‘EB’ = Echo Blue and ‘ABC’ = ‘ABC’ 2 Blue. Blue dashed line represents minimum length to be considered marketable (30 cm) (Barr, 1992)

In the field, no significant differences were observed between cultivars (Figure 16). Average stem length (19.6 to 26.4 cm) for all three cultivars in 2016 Absaraka failed to meet minimum market standards. All three cultivars in 17A and 16W met minimum market standards while only two of the three cultivars in 17W met market standards.

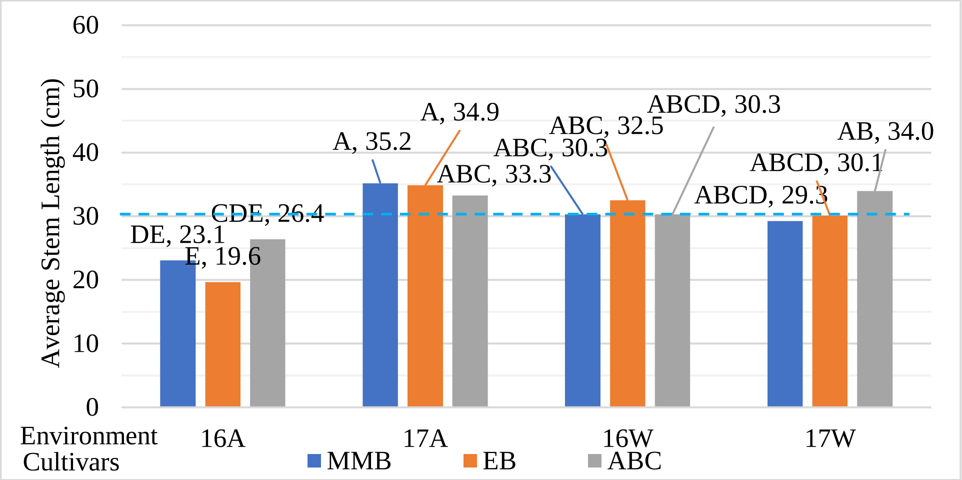

Figure 16. Interaction of Environment (Location by Year) and Cultivar on Average Lisianthus Stem Lengths Harvested in the Field. Mean totals with a common letter are not different ($P \leq 0.05$) by Tukeys HSD test (n= 6). Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston, 'MMB' = Mariachi Misty Blue, 'EB' = Echo Blue and 'ABC' = 'ABC' 2 Blue. Blue dashed line represents minimum length to be considered marketable (30 cm) (Barr, 1992).

Stem Caliper

A three-way interaction occurred between soil temperature, cultivar, and environment for average stem caliper of high tunnel grown cut flowers. The interaction of cultivar by environment was significant for average stem caliper of field grow flowers (Appendix A7). In the high tunnel, only one cultivar in one environment showed a response to soil temperature at transplanting. 'EB' in 2016 Williston showed a 25% increase when transplanting was delayed from 13 °C (4.1 mm) to 18 °C (5.2 mm) (Figure 17). No other cultivar differences emerged for the rest of the environments; however significant environmental differences were observed. In 2016 Absaraka under both transplanting temperatures, the greatest average stem caliper occurred for all three cultivars, with calipers ranging from 6.3 to 6.7 mm. Under the 13 °C transplanting temperature, all cultivars in the remaining environments produced average stem calipers that met the minimum market standard. Under the 18 °C temperature, ‘MMB’ didn’t meet minimum market standards for 2017 Absaraka and 2017 Williston.

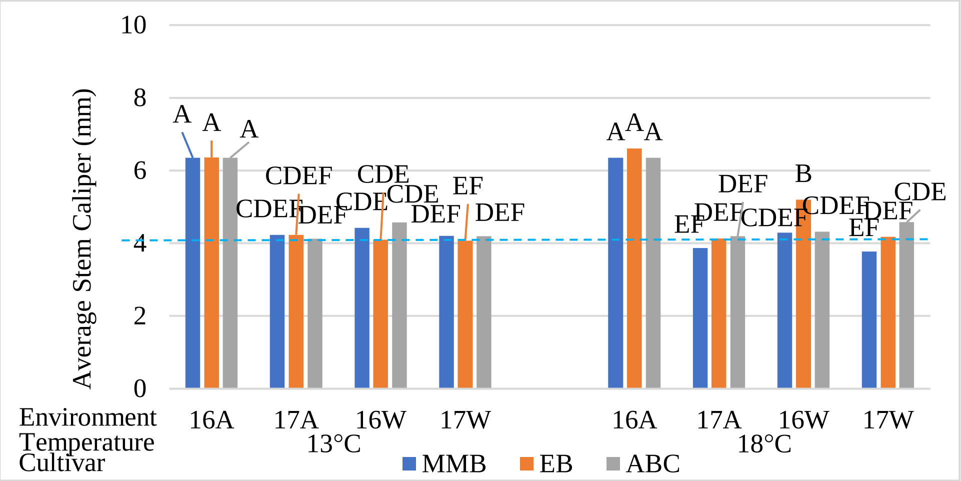

Figure 17. Interaction of Environment (Location by Year), Cultivar, and Temperature on Average Lisianthus Stem Caliper Harvested in the High Tunnel. Mean totals with a common letter are not different ($P \leq 0.05$) by Tukeys HSD test (n= 6). Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston, ‘MMB’ = Mariachi Misty Blue, ‘EB’ = Echo Blue and ‘ABC’ = ‘ABC’ 2 Blue. Blue dashed line represents minimum caliper to be considered marketable (4 mm) (Barr, 1992).

A two-way interaction occurred for average field-grown lisianthus stem caliper. Cultivar differences occurred within three of the four environments (Figure 18). In 2017 Absaraka, ‘MMB’ produced the greatest average stem caliper of 5.6 mm. Average stem caliper for ‘MMB’ was significantly shorter in the other three environments. ‘EB’ produced its largest average caliper, in 2016 across both locations, ranging from 5.2 to 5.9 mm. In 2017, average caliper for “EB’ ranged from 3.9 to 4.0 mm, a 37% reduction compared to 2016. ‘ABC’ showed no differences between environments with calipers ranging from 3.6 to 4.4 mm.

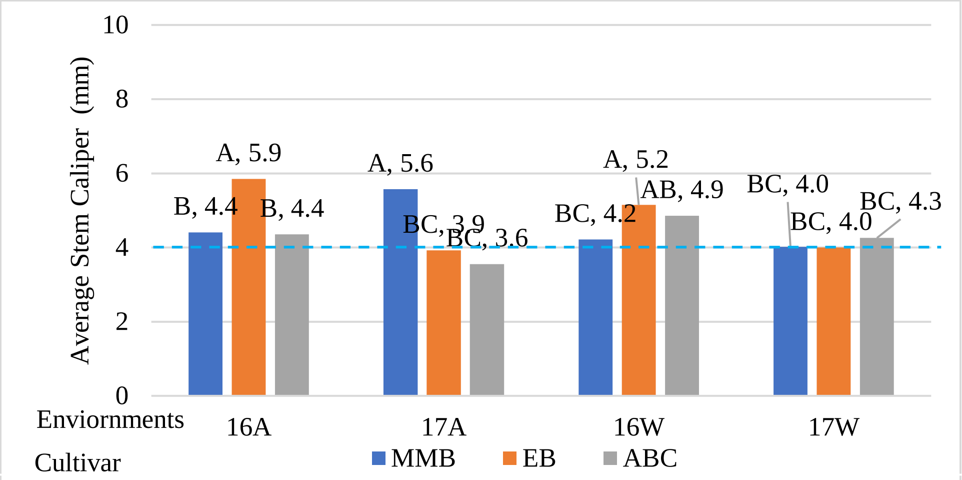

Figure 18. Interaction of Environment (Location by Year) and Cultivar on Average Stem Caliper of Lisianthus Harvested in the Field. Mean totals with a common letter are not different ($P \leq 0.05$) by Tukeys HSD test (n= 6). Abbreviations: 16A= 2016 Absaraka, 17A= 2017 Absaraka, 16W= 2016 Williston, 17W= 2017 Williston, 'MMB' = Mariachi Misty Blue, 'EB' = Echo Blue and 'ABC' = 'ABC' 2 Blue. Blue dashed line represents minimum caliper to be considered marketable (4 mm) (Barr, 1992).

Discussion

High Tunnel

Looking at the average number of stems produced in the high tunnel through the interaction of soil temperature at transplanting by environment, we see that a response to soil temperature at transplanting was only observed in 2017. One possible cause is that both high tunnels were constructed in late April 2016 which reduced the opportunity for early season heating. In comparison the 2017 environments were able to capitalize on the benefits of passive solar heating earlier for the entire spring. This is evident when examining planting dates from 2016 to 2017 in all environments (Table 1) as well as GDU (Appendix B2). On average in 2017, plant materials were planted 26 d earlier than in 2016, allowing more time for growth and maturation. Overall the 2017 Williston location produced more flower stems compared to 2017 Absaraka. However, roughly the same percentage decrease in average number of stems harvested (30 to 32%) was observed when transplanting occurred at the higher soil temperature over both locations. This result highlights the need for accurate timing of transplanting to maximize stem production by taking advantage of early heating in the spring and a longer growing season.

The 2016 Williston environment as well as Absaraka in 2017 when planted at 18°C saw reduced stems harvested compared to the other environments, when examining environmental data including: ADT, DIF (Appendix A2) MAX, and MIN (Appendix A3) we see that almost immediately after transplanting excessive temperatures above 22°C were experienced after transplanting, likely causing rosetting of lisianthus cultivars. Harbaugh et al., (1992) found, that as soil temperature increased, the percentage of rosetting for all cultivars also increased. With soil at 31°C, producing 83%, 58%, 19%, and 2% of the rosetted seedlings for the cultivars USDA-Pink, Yodel White, Little Belle Blue, and GCREC-Blue, respectively (1992). Further research conducted in a greenhouse by (Harbaugh et al., 2000) evaluated forty-seven cultivars of lisianthus as cut flowers finding significant variation in sensitivity at level to rosetting when exposed to temperatures of 22°C. Cultivars chosen in our study were reported to have 8-32 % of seedling rosetted, with the best cultivars having 0-2% of seedling rosetted. No cultivar differences emerged in the high tunnel regarding average total stems. Ortiz et al., in 2012 reported that production densities for Eustoma 'Mariachi Blue' when grown the high tunnel of 90 stems m^{-2}. Our experiment produced three environments, when transplanted at 13°C soil temperature, well in excess of a 100 stems, as well as the previous study, ranging from 120 to 216 stems m^{-2}. At 18°C only two environments were in excess of 100 stems ranging from 140 to 146 stems m^{-2}. This suggests that the Northern Great Plains might have the advantage of increased production densities, even when transplanting was not optimized, but also have the increased potential of rosetting with certain cultivars.

Cultivar differences, however, did emerge with regards to lisianthus stem lengths when grown in the high tunnel. ‘MMB’ produced the longest average stem length of the experiment at the Absaraka location (42.1 to 44.7 cm), producing 11% longer stems than the Williston location. Echo Blue did not show any preference for environments, while ‘ABC’ produced similar lengths to the other cultivars in only the 16A environment. The remaining environments displaying a 19% decrease from 16A as well as falling below market quality. An evaluation of forty-seven cultivars of lisianthus as cut flowers conducted found that the average heights of cultivars in their study was between 113 to 126 cm, with Echo Blue producing the longest lengths on average (Harbaugh et al., 2000). Ortiz et al., in 2012 reported average stem lengths for lisianthus ‘Mariachi Blue’ grown in the high tunnel of 66.7 cm. Compared to both previous studies, average stem lengths of lisianthus in the NGP were reduced, however for the cultivars ‘MMB’ and ‘EB’ production was still above marketable quality in all environments. One possible explanation for the reduced stem lengths overall might be that each of the high tunnels were covered in a 6 mm exterior polyethylene film and a 4 mm interior polyethylene film and ultraviolet additives with a reported 90% light transmission, which could possibly be altering the relative transmission of red and far-red light. A study reported three lisianthus cultivars Flamenco Red, Mirage Pastel, and Flamenco Purple when grown under black shade-netting which allowed 54% light transmission without altering spectra, produced significant differences in the numbers of flowers as well as stem lengths between the three cultivars (Ovadia et al., 2015).

Despite the decreased light transmission overall, when comparing the data for all three cultivars, we see stem lengths ranging from 53.3-67.2 cm, still in excess of our data. Suggesting in fact that the red: far red (R:FR) ratio and not percent of light transmitted might be responsible for decreased stem lengths of lisianthus in the high tunnel. Several studies have demonstrated the effect of selective filtration of sunlight on the growth and development of ornamental plants. Light-filtering plastic films containing pigments that increased the R:FR ratio had a dwarfing effect on gardenia, chrysanthemum, cosmos, and zinnia plants (McMahon and Kelly, 1995). While films that decreased the R:FR ratio caused an increase in chrysanthemum height but had no effect on zinnia or cosmos plants (Cerny et al., 2003; Lykas et al., 2006). Colored shade-nettings were found to have a significant effect on the growth characteristics of lisianthus flowers (Ovadia et al., 2015). Longer flowering stems were seen in plants grown under yellow and red shade-nets, compared to the black netting. This increase in length was accompanied by a significantly higher cut stem weight under the yellow and red nets, compared to both the blue and black nettings. The use of photo-selective filters may serve to control and improve the growth, development, and flowering of lisianthus in the high tunnel.

The three-way interaction of cultivar by temperature by environment was significant for stem calipers grown in the high tunnel however only one cultivar, Echo Blue in one environment showed sensitivity when delaying transplanting. This suggest that there under certain conditions delaying transplanting could improve stem caliper quality however this effect appears to be cultivar specific and intermittent at best. The largest calipers were observed in 2016 Absaraka location across both transplanting temperatures ranging from 6.3 to 6.7 mm. Ortiz et al., in 2012 reported average stem calipers for lisianthus ‘Mariachi Blue’ grown in the high tunnel of 9.2 mm and 8.9 mm in the field nearly a 40% increase over our experiments. To our knowledge, no other replicated cut flower trial for lisianthus has been conducted while reporting stem caliper.

Field

Looking at total stem production of the field through the interaction of cultivar by environment, we see that individual cultivar differences along with the greatest amount of average total stems only emerged in the Williston environments. In 2016 ‘MMB’ and in 2017 ‘EB’ had stem densities ranging from 96 to 102 stems m^{-2}. These results generally align with climatic norms of Williston experiencing an average increase of 250 growing degree units over Absaraka (National Oceanic and Atmospheric Administration, 2013). When comparing growing degree units (Appendix B2). we see significant environmental inconsistencies during both years not completely aligning with the 30-year averages (Appendix A4, A5). All environments experienced between a 10-26% decrease from the norm's, with 17W accumulating the most GDUs during the growing season (May to November), followed by 16A, 16W, and 17A respectively. This result highlights the increasing variability of the regional NGP climates and the need for expansive and continuing cultivar evaluation at the regional level. Previous work conducted by Starman et al., 1995 reported for 'Yodel Blue' 30.3 stems m^{-2}. Ortiz et al., (2012) reported increases compared to the previous densities for lisianthus 'Mariachi Blue' when grown the field of 89.3 stems equal to production in the high tunnel in their experiment. Our experiment only produced 4 out of twelve unique cultivar by environmental combinations that are congruent with Ortiz et al., 2012 results all of them occurring in Williston. The rest of by environment combinations produced 46 to 70 stems in-between densities of both previous studies. Anecdotally comparing this to the high tunnel results we see roughly a 50% decrease in average total stems from the most productive environments and a 75% reduction for the lesser productive environments in the field. Although not directly compared in our study due to limitations of space and funding, our experiments suggest that significant differences in total stem production overall exist between the field and high tunnel for lisianthus produced in the NGP's. The main effect of soil temperature at transplanting was also significant for average number of stems of lisianthus grown in the field. The same trend of decreased average total stems harvested was observed when transplanting was delayed as in the high tunnel, albeit to a lesser degree 13% vs 31%. The effect reduced overall but still reinforces the importance of transplanting at the correct time to maximize yield even in the field.

In the bulk of environments average stem lengths were similar ranging from 29.3 to 35 cm, with the outlier of 2016 Absaraka producing below market quality lengths of 19.6 to 24 cm. Starman et al., 1995 reported for ‘Yodel Blue’ produced in average stem lengths of 45 cm. Ortiz et al., in 2012 reported an increase in average stem lengths for lisianthus ‘Mariachi Blue’ grown in the field of 52 cm a 22% decrease from stem lengths grown in the high tunnel in the same experiment. Our findings are reduced compared to both previous results. When anecdotally comparing high tunnel overall stem lengths are decreased from 4 to 11% in the field, which is in line with the previous research findings (Wien, 2009; Ortiz et al., 2012). However, on a cultivar basis Echo blue produced longer stem lengths in three out of four environments in the field. This result illustrates the harsh and variable nature of production in the Northern Great Plains.

Stem caliper was variable for by environment interaction in the field, the largest calipers in the experiment were found in 2016 at both location for ‘EB’ and in 2017 Absaraka for ‘MMB’. Production ranged from 5.2 to 5.9 mm for the most productive environments, with the remaining combinations averaging between 3.6 to 4.9 mm. Ortiz et al., in 2012 reported average stem calipers for lisianthus ‘Mariachi Blue’ of 8.9 mm when grown in the field nearly a 36 % increase over the most productive combinations in this experiment and 47% increase over the remaining environments.

Conclusion

Production of lisianthus is feasible in the Northern Great Plains, but potential issues with quality may occur when field grown. Both average stem length and caliper were reduced compared to previous field research. Additionally, field produced flowers failed to reach marketable lengths in one out of four environments and two out of twelve cultivar by environment combinations failed to reach marketable calipers. Average number of stems were lower in the majority of cultivar by environment combinations compared to the previous work and when compared to the high tunnel.

Lisianthus are better suited for production in the high tunnel for the NGP. Average number of stems were higher in the high tunnel compared to previous research. However, the potential for rosetting appears to be a significant concern. Further testing and selection for rosetting resistance is needed. The high tunnel produced longer average stem length, above market quality, for the cultivars MMB and EB. However, ‘ABC’ in three high tunnel environments failed to meet market quality compared to only one environment which did not meet quality standards in the field further illustrating the variable nature of production in the NGP and the need for expansive regional testing of cultivars in a variety of production methods. Based on our results, ‘MMB’ and ‘EB’ are recommended for high tunnel production, while ‘ABC’ appears suitable for field production.

Soil temperature at transplanting influenced average total stem production and this was significant in both production methods. When transplanting was delayed, the number of harvested stems decreased. Further research is needed to refine the ideal temperature at transplanting to maximize yields.

GENERAL SUMMARY

Dahlia, snapdragon, and lisianthus all appear to be best suited for production in the high tunnel in the NGP. High tunnel environments have a longer spring growing season compared to the field. Average number of stems harvested increased when compared to field production; however, variation was still observed between years which was attributed to the high tunnel construction in late April 2016. Average stem length and caliper were varied, for dahlia and snapdragons, stem lengths and calipers were increased in the high tunnel compared to the field. Lisianthus had one cultivar (ABC) which produced greater stem lengths in the field. No clear preference for cultivar emerged in the high tunnel for dahlia or snapdragon, while for lisianthus the cultivars MMB and EB are recommended for production in the high tunnel.

Production of cut flowers in the field is feasible throughout the NGP for all species investigated; however, cut flowers averaged on the low end of marketability standards. Dahlia and snapdragon stems harvested were equivalent or greater than previous research into field production carried out in other regions of the US, while stems harvested for lisianthus were lower than previous research. For field production dahlia ‘Irene’, snapdragon ‘RM’, and lisianthus ‘ABC’ are recommended for production in the NGP. Temperature at transplanting’s effect on average total stem m^{-2} was significant for both the high tunnel and the field, when transplanting was delayed the number of harvested stems decreased.

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APPENDIX A

Table A1. Analysis of Variance for Average Stems, Stem Length, and Caliper for Dahlias Produced in The High Tunnel and Field in 2016 and 2017.

High Tunnel			
Effects	Average stems	Stem length	Stem Caliper
	Pr > F		
Temperature	NS	NS	*
Environment	*	**	NS
Cultivar	NS	NS	NS
Temp*Environment	NS	NS	NS
Cultivar*Environment	NS	NS	*
Temp*Cultivar	NS	NS	NS
Temp*Cultivar*Environment	NS	NS	NS

Field			
Effects	Average stems	Stem length	Stem Caliper
	Pr > F		
Temperature	NS	NS	NS
Environment	*	**	NS
Cultivar	NS	NS	NS
Temp*Environment	NS	NS	NS
Cultivar*Environment	***	**	NS
Temp*Cultivar	**	NS	NS
Temp*Cultivar*Environment	NS	*	NS

***, **, * Significant at P # 0.001, 0.01, 0.05. NS = nonsignificant

Table A2. Average Daily Temperature, Average Daily Soil Temperature (°C) Within 15 cm of the Surface, and Daily Light Integral Observed in the High Tunnel and Field Environments In 2016 and 2017.

	Average Daily Temperature (°C)				Average Daily Soil Temperature (°C)				Daily Light Integral (mol • m^2 • d^{-1})			
	Field											
Month	16A	17A	16W	17W	16A	17A	16W	17W	16A	17A	16W	17W
April	8.6 (±3.1)	12.8(±4.0)	8.0(±3.6)	6.1(±4.1)	8.4(±1.5)	7.1(±2.9)	9.2(±3.1)	8.7(±2.3)	40.2(±11.9)	36.2(±13.6)	40.4(±13.1)	43.4(±9.7)
May	15.0 (±4.5)	18.7(±3.5)	14.1(±4.3)	14.1(±3.7)	14.4(±1.9)	14.2(±2.1)	16.9(±3.2)	16.5(±2.4)	44.7(±10.4)	43.1(±11.7)	49.1(±6.1)	46.5(±10.1)
June	19.5 (±3.0)	20.3(±3.1)	19.3(±2.4)	18.6(±2.9)	21(±1.9)	19.9(±0.9)	22.7(±1.8)	22.2(±2.3)	41.0(±10.7)	45.0(±10.2)	42.7(±9.3)	45.8(±9.3)
July	21.1 (±2.4)	18.7(±2.1)	21.3(±2.8)	24.4(±2.4)	22.2(±1.5)	22.5(±1.2)	23.7(±2.7)	27.8(±1)	38.3(±8.4)	36.2(±11.2)	39.0(±6.4)	36.4(±9.1)
August	20.3 (±2.5	16.5(±3.6)	21.1(±2.8)	20.0(±2.6)	22.4(±1.2)	20.2(±0.8)	24.2(±1.1)	21(±1.1)	25.4(±9.6)	24.9(±12.4)	23.7(±10.3)	23.8(±12.2)
September	15.9(±3.4)	9.8(±3.5)	15.3(±3.8)	14.5(±5.1)	17.1(±1.7)	17.8(±1.7)	16.4(±1.5)	17.7(±3.6)	15.0(±7.7)	18.6(±7.7)	14.2(±6.5)	18.4(±6.4)
October	8.3 (±4.8)	-3.4(±4.7)	7.8(±4.6)	7.2(±4.8)	9.1(±1.7)	10.1(±1.6)	8(±1.6)	8.7(±1)	11.4(±6.3)	10.4(±4.1)	10.4(±5.2)	10.6(±3.9)
November	4.5 (±4.8)	0.2(±1.4)	4.1(±4.9)	-2.6(±6.1)	5.8(±2.5)	0.1(±0.6)	5.3(±2.1)	-0.5(±1.1)	8.9(±3.2)	8.8(±3.2)	8.2(±2.7)	8.2(±2.7)
	High Tunnel											
April	9.3(±4.5)	21.2(±4.7)	9.1(±7.7)	20.3(±4.7)	9.1(±2.3)	21.7(±3.1)	10.3(±5.9)	23(±2.8)	32.4(±9.5)	29.0(±10.8)	32.7(±10.7)	35.4(±8.2)
May	25.7(±2.4)	23.9(±3.4)	24.7(±4.5)	25.2(±3.6)	27(±2.1)	23.9(±2.3)	27.9(±3.5)	27.6(±2)	36.2(±8.2)	34.7(±9.5)	40.0(±5.6)	37.5(±8.2)
June	24.8(±2.8)	24.4(±3.2)	24.6(±2.4)	23.9(±2.9)	27.3(±2.4)	24.7(±1.3)	28.4(±1.8)	28.5(±2)	33.2(±8.6)	36.5(±8.5)	34.6(±7.6)	37.4(±7.8)
July	26.2(±2.8)	26.3(±2.7)	26.4(±2.8)	29.5(±2.4)	27.7(±2.4)	27.9(±1.1)	30.1(±2.6)	32.4(±1.5)	31.1(±6.9)	29.2(±9.2)	31.5(±5.2)	29.5(±7.4)
August	20.3(±0.9)	22.9(±1.4)	25.9(±2.8)	24.7(±2.5)	21.8(±1.6)	24.9(±0.9)	28.2(±1.3)	29.6(±1.3)	20.6(±7.9)	20.0(±10.0)	19.2(±8.3)	19.2(±9.9)
September	19.5(±1.3)	19.9(±3.8)	19.9(±3.8)	18.7(±5.2)	19.3(±2)	20.9(±2.3)	20.1(±1.6)	20.2(±3.8)	12.1(±6.2)	15.1(±6.2)	11.5(±5.3)	14.9(±5.2)
October	16.5(±2.6)	12.1(±5.7)	12.4(±4.6)	11.4(±4.8)	17.2(±3.4)	12.9(±2.7)	12.5(±1.3)	11.9(±2)	9.2(±5.1)	8.4(±3.3)	8.5(±4.2)	8.5(±3.2)
November	8.6(±9.2)	1.2(±4.5)	8.7(±4.9)	1.8(±6.2)	8.5(±7.4)	4.4(±0.5)	8.5(±2.5)	4.7(±1.6)	7.2(±2.6)	7.1(±2.6)	6.6(±2.1)	6.6(±2.2)

The four environments are represented by year (2016 or 2017) and location (A is for Absaraka and W is for Williston

Table A3. Average Daily Maximum and Minimum Temperatures (°C) As Well As Di-Urinal Swing Observed Per Month in The High Tunnel and Field Environments (Location by Year).

	Minimums (°C)				Maximums (°C)				Average DIF(°C)			
	Field											
Month	16A	17A	16W	17W	16A	17A	16W	17W	16A	17A	16W	17W
April	-8.2(±4.4)	-4.1(±3.3)	-0.6(±1.7)	-7.6(±3.9)	20.7(±5.5)	25.4(±6.1)	25.4(±6.1)	20.7(±5.5)	11.8(±6.2)	12.4(±5.4)	11.1(±5.4)	12.4(±4.4)
May	-4.7(±5.4)	-0.3(±3.5)	-0.1(±4.0)	0.5(±3.4)	31.6(±4.7)	32.1(±5.5)	32.1(±5.5)	31.6(±4.7)	15.8(±5.8)	15.1(±5.1)	14.1(±4.5)	15.1(±3.3)
June	6.9(±3.6)	4.5(±3.0)	4.9(±2.3)	4.8(±2.9)	33.4(±4.0)	34.6(±3.2)	34.6(±3.2)	33.4(±4.0)	12.4(±4.0)	14.8(±4.4)	13.2(±2.8)	15.2(±3.8)
July	5.7(±2.7)	7.4(±2.9)	10.0(±2.3)	12.4(±2.0)	38.5(±3.6)	36.4(±3.8)	36.4(±3.8)	38.5(±3.6)	12.5(±3.0)	14.3(±3.1)	13.3(±3.0)	16.1(±3.1)
August	6.2(±3.2)	6.1(±2.4)	7.8(±2.5)	6.6(±2.3)	35.0(±3.8)	37.0(±4.1)	37.0(±4.1)	35.0(±3.8)	14.6(±3.0)	13.5(±4.0)	15.8(±3.7)	14.5(±3.7)
September	-0.2(±4.3)	1.8(±3.7)	-0.9(±3.7)	1.0(±3.4)	34.9(±7.6)	33.5(±5.4)	33.5(±5.4)	34.9(±7.6)	13.2(±3.9)	13.4(±6.1)	12.4(±5.3)	12.8(±5.8)
October	-5.7(±5.1)	-11.6(±5.5)	-4.6(±3.8)	-10.6(±4.0)	26.2(±6.1)	25.3(±6.3)	25.3(±6.3)	26.2(±6.1)	12.1(±5.0)	15.1(±5.0)	10.2(±4.8)	14.9(±4.5)
November	-0.8(±3.2)	-8.7(±4.8)	-1.4(±3.4)	-8.9(±5.8)	26.2(±7.3)	24.0(±7.1)	24.0(±7.1)	26.2(±7.3)	12.0(±5.8)	15.0(±4.9)	10.1(±5.0)	15.0(±5.1)
	High Tunnel											
April	-8.2(±6.0)	10.8(±4.1)	-7.5(±8.21)	10.6(±4.5)	35.8(±5.9)	35.8(±5.9)	28.1(±7.7)	31.8(±5.5)	11.1(±6.2)	6.5(±3.8)	10.4(±4.0)	6.0(±3.3)
May	13.2(±3.4)	14.3(±3.2)	14.5(±4.05)	15.0(±3.2)	38.3(±4.9)	38.3(±4.9)	39.3(±5.5)	38.8(±4.7)	8.9(±5.3)	8.1(±4.6)	7.2(±3.6)	7.7(±3.3)
June	10.3(±2.6)	6.5(±3.0)	6.9(±2.34)	6.7(±2.8)	45.0(±4.6)	45.0(±4.6)	43.2(±3.2)	42.1(±4.0)	19.1(±4.5)	21.4(±4.4)	19.9(±2.8)	21.9(±3.8)
July	10.5(±2.2)	10.0(±3.0)	12.7(±2.37)	15.0(±2.0)	43.3(±3.2)	43.3(±3.2)	43.9(±3.8)	46.1(±3.5)	17.4(±4.8)	19.2(±3.2)	18.2(±3.0)	21.1(±3.1)
August	15.9(±1.2)	9.4(±2.4)	11.1(±2.48)	9.9(±2.3)	36.7(±2.6)	36.7(±2.6)	43.3(±4.1)	41.3(±3.8)	2.1(±2.9)	16.6(±4.0)	18.8(±3.7)	17.5(±3.7)
September	15.4(±1.5)	5.8(±3.7)	3.1(±3.69)	4.9(±3.4)	39.3(±5.9)	39.3(±5.9)	38.9(±5.4)	40.3(±7.6)	2.6(±3.2)	14.9(±6.1)	13.8(±5.3)	14.3(±5.8)
October	8.6(±3.1)	-7.0(±5.5)	0.1(±3.73)	-6.0(±4.2)	29.9(±6.8)	29.9(±6.8)	30.7(±6.4)	30.7(±6.1)	4.0(±2.1)	15.0(±4.9)	10.1(±4.9)	14.9(±4.4)
November	5.1(±10.9)	-4.1(±4.8)	3.2(±3.38)	-4.1(±5.8)	29.9(±5.5)	29.9(±5.5)	28.5(±7.1)	30.7(±7.3)	4.0(±4.1)	14.9(±4.9)	10.0(±5.0)	14.9(±5.1)

The four environments are represented by year (2016 or 2017) and location (A is for Absaraka and W is for Williston

Table A4. Summary of Growing Degree Unit Monthly Normal From 1981 to 2010 for the Casselton Agronomy Farm.

Growing Degree Units Monthly

Base °C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4.4	1	2	24	124	286	421	545	530	331	139	19	1
7.2	0	1	9	72	206	338	459	444	251	83	8	0
10.0	0	0	3	36	133	255	373	358	176	42	3	0
12.8	0	0	1	14	74	175	287	273	110	18	1	0
15.6	0	0	0	4	33	104	202	191	61	6	0	0

Growing Degree Units Accumulated Monthly

Base °C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4.4	1	3	27	152	438	858	1403	1933	2264	2403	2423	2423
7.2	0	1	9	81	287	624	1083	1527	1778	1861	1869	1869
10.0	0	0	3	39	172	427	800	1158	1334	1376	1379	1379
12.8	0	0	1	15	89	264	551	824	934	952	953	953
15.6	0	0	0	4	38	142	344	534	595	601	601	601

Data adapted from National Oceanic & Atmospheric Administration, National Environmental Satellite, Data, and Information Service station reports. Highlighted row represents base temperature used in this experiment.

Table A5. Summary of Growing Degree Unit Monthly Normal From 1981 to 2010 for the Williston Experimental Farm.

Growing Degree Units Monthly

Base °C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4.4	0	0	9	98	281	427	521	492	311	119	13	0
7.2	0	0	2	56	202	343	435	406	230	69	4	0
10.0	0	0	1	27	131	261	349	320	157	36	1	0
12.8	0	0	0	12	73	181	263	235	93	16	0	0
15.6	0	0	0	4	34	108	178	153	47	6	0	0

Growing Degree Units Accumulated Monthly

Base °C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4.4	0	0	9	107	388	814	1336	1828	2138	2257	2270	2270
7.2	0	0	2	58	259	603	1038	1444	1674	1743	1747	1747
10.0	0	0	1	28	158	419	768	1088	1244	1280	1281	1281
12.8	0	0	0	12	85	266	528	763	857	872	872	872
15.6	0	0	0	4	38	146	324	478	525	531	531	531

Data adapted from National Oceanic & Atmospheric Administration, National Environmental Satellite, Data, and Information Service station reports. Highlighted row represents base temperature used in this experiment.

Table A6. Analysis of Variance for Average Stems, Stem Length, And Caliper for Snapdragons Produced in The High Tunnel and Field In 2016 and 2017.

High Tunnel			
Effects	Average stems	Stem length	Stem Caliper
	Pr > F		
Temperature	NS	NS	NS
Environment	*	*	***
Cultivar	*	*	NS
Temp*Environment	NS	NS	NS
Cultivar*Environment	NS	NS	**
Temp*Cultivar	NS	NS	*
Temp*Cultivar*Environment	NS	NS	NS

Field			
Effects	Average stems	Stem length	Stem Caliper
	Pr > F		
Temperature	NS	NS	NS
Environment	*	NS	NS
Cultivar	NS	NS	NS
Temp*Environment	NS	NS	NS
Cultivar*Environment	***	NS	NS
Temp*Cultivar	*	NS	NS
Temp*Cultivar*Environment	NS	NS	NS

***, **, * Significant at P # 0.001, 0.01, 0.05. NS = nonsignificant.

Table A7. Analysis of Variance for Average Stems, Stem Length, And Caliper for Lisanthus Produced in The High Tunnel and Field In 2016 and 2017.

High Tunnel

Effects	Average stems	Stem length	Stem Caliper
		Pr > F	
Temperature	NS	NS	NS
Environment	*	*	*
Cultivar	NS	NS	NS
Temp*Environment	**	NS	NS
Cultivar*Environment	NS	*	**
Temp*Cultivar	NS	NS	*
Temp*Cultivar*Environment	NS	NS	*

Field

Effects	Average stems	Stem length	Stem Caliper
		Pr > F	
Temperature	**	NS	NS
Environment	*	**	NS
Cultivar	NS	NS	NS
Temp*Environment	NS	NS	NS
Cultivar*Environment	***	**	**
Temp*Cultivar	NS	NS	NS
Temp*Cultivar*Environment	NS	NS	NS

***, **, * Significant at P # 0.001, 0.01, 0.05. NS = nonsignificant.

APPENDIX B

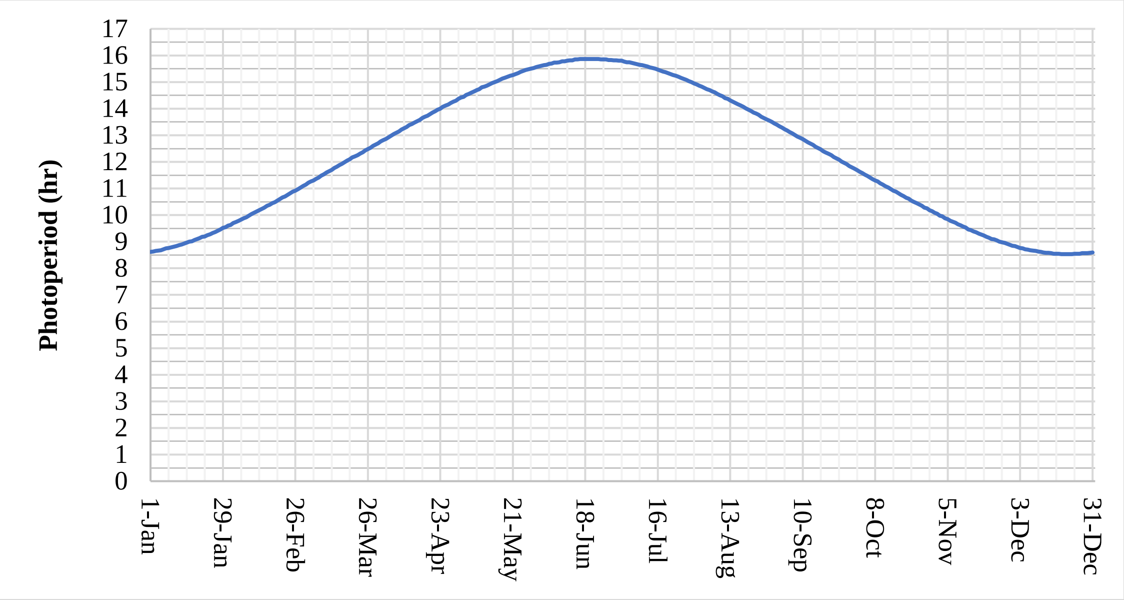
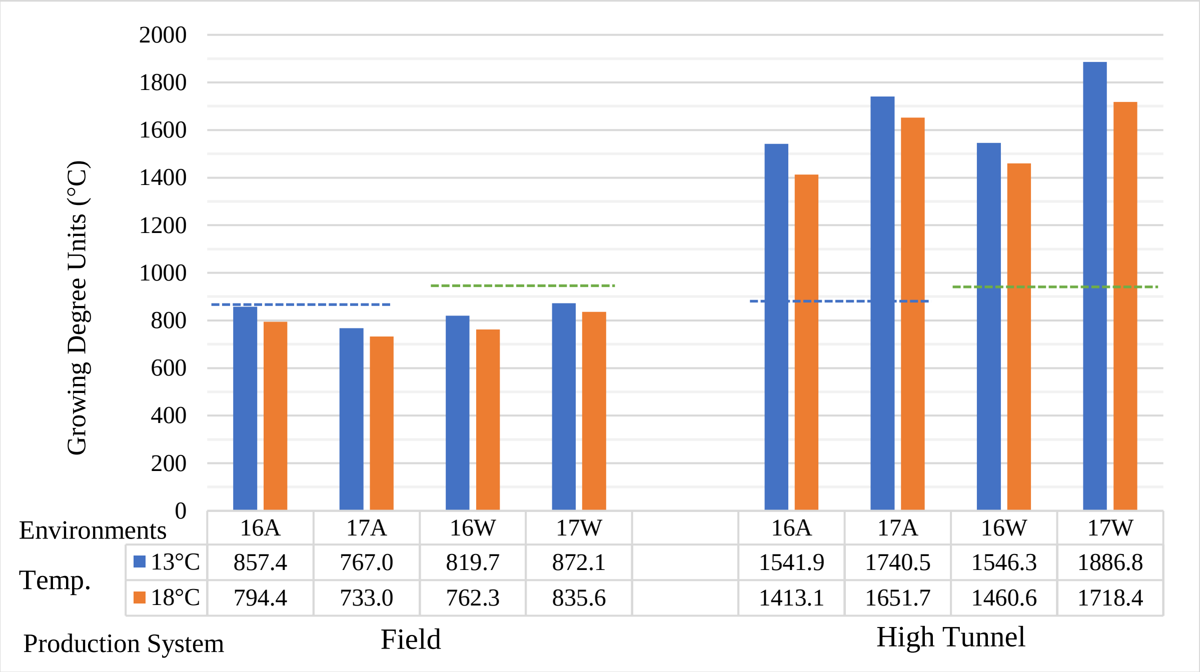


Figure B1. Photoperiod Through Time for the Northern Great Plains. Adapted from National Oceanic &and Atmospheric Administration serial complete data.



Environments		16A	17A	16W	17W		16A	17A	16W	17W
Temp.	🟦 13°C	857.4	767.0	819.7	872.1		1541.9	1740.5	1546.3	1886.8
	🟧 18°C	794.4	733.0	762.3	835.6		1413.1	1651.7	1460.6	1718.4
Production System		Field					High Tunnel			

Figure B2. Growing Degree Units of the High Tunnel and Field in various environments. Absaraka and Williston, North Dakota in 2016 and 2017. The four environments are represented by year (2016 or 2017) and location (A is for Absaraka and W is for Williston). Blue and green dotted lines represent 30-year averages of growing degree day derived from NOAA serial complete data for respective locations.

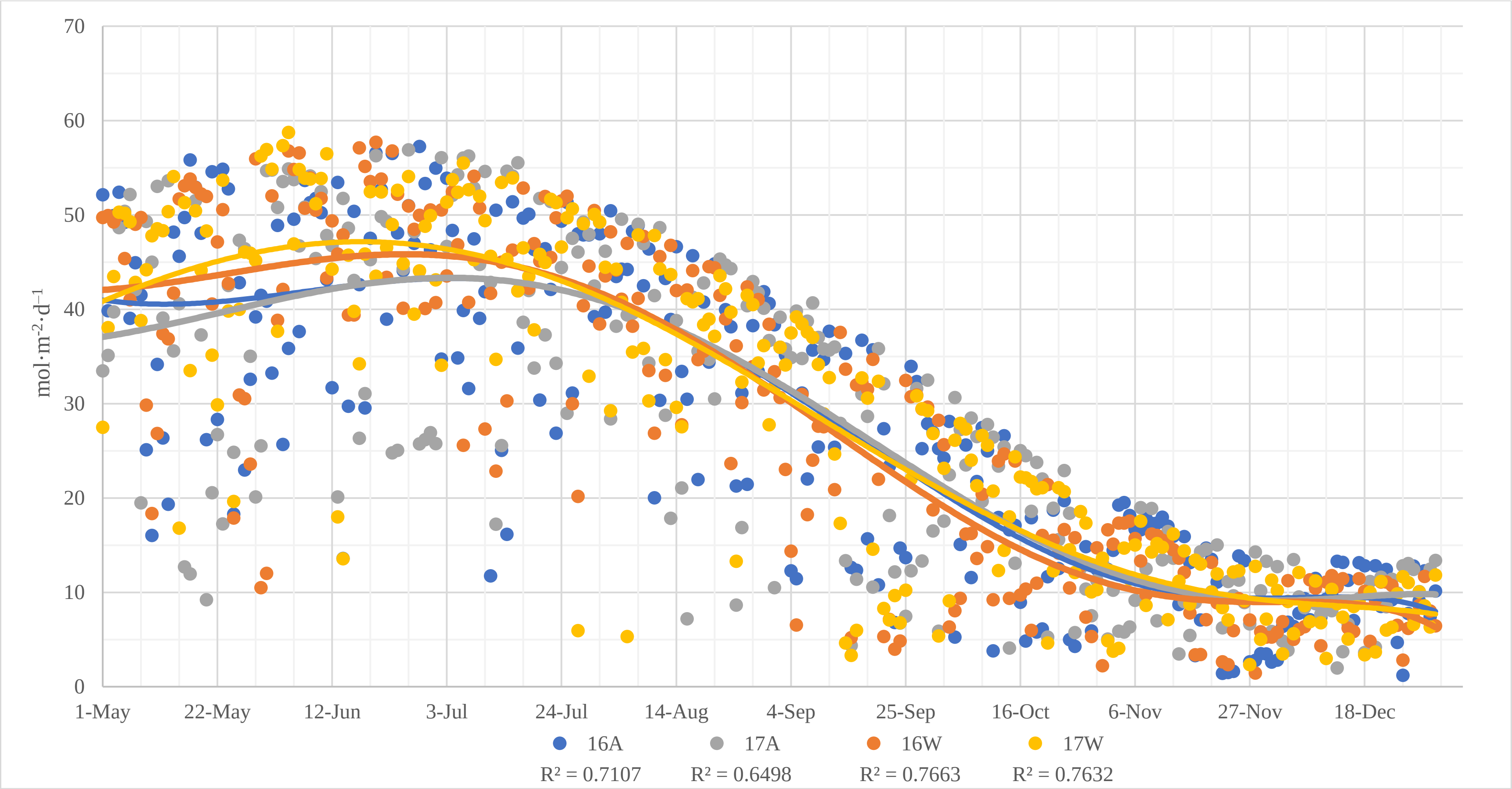


Figure B3. Daily Light Integral Observed in Absaraka and Williston, North Dakota in 2016 and 2017. The four environments are represented by year (2016 or 2017) and location (A is for Absaraka and W is for Williston). Solid lines represent polynomial trend line with r^2 values blow respective environments