HIGH TUNNELS EXTEND THE GROWING SEASON IN WARM SEASON CROPS TOMATO, CUCUMBER AND BELL PEPPER

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

Kyla Louise Splichal

In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Plant Sciences

April 2020

Fargo, North Dakota

North Dakota State University
Graduate School

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

High tunnels are used to modify the crop environment by trapping solar energy, providing protection from unfavorable weather events, and extending the growing season in temperate regions. This project assessed yield and quality in three independent cultivar trials of warm-season crops tomato (*Solanum lycopersicum* L.), bell pepper (*Capsicum annuum* L.) and cucumber (*Cucumis sativus* L.) grown under high tunnel production compared with an outdoor field in eastern and western North Dakota. Tomato yields in the high tunnel were increased by 1.4 times over the field trial yields. Yields from the pepper cultivar trials both inside the high tunnel and outside field were comparable to one another at 1.24 kg plant^{-1} and 1.06 kg plant^{-1}, respectively. Cucumber yields in the high tunnel were increased by 1.7 times over the field trial yields. Results indicate that in North Dakota, high tunnels extended the growing season, and increased production relative to field conditions.

ACKNOWLEDGEMENTS

I would like to start off with a sincere acknowledgement of thanks to my advisors, Dr. Harlene Hatterman-Valenti and Dr. McGinnis and committee member, Dr. Janet Knodel for agreeing to be a part of this process. Thank you to both Dr. Harlene Hatterman-Valenti and Dr. Esther McGinnis for giving me the opportunity to showcase my leadership skills by encouraging me to take on this project as the principal investigator with the granting agency. Thank you, Harlene for your continued guidance both in my graduate and undergraduate studies at North Dakota State University and your willingness drop everything to provide advice, support and encouragement.

I would also like to thank my colleagues at the Williston Research Extension Center who have either played an integral role in the development of this project or provided support of the research objectives by imparting relevant knowledge in each of their respective fields: Irrigation Scientist, Tyler Tjelde; Agronomist, Dr. Gautam Pradhan; Pathologist, Dr. Audrey Kalil, and Area Extension Specialist, Dr. Clair Keene.

A special thank you goes to Tyler Tjelde and the entire staff at Nesson Valley. Tyler’s unique perspective on irrigation techniques, extensive farming experience and the practical way in which he solves problems made this project a tremendous success. Thank you for your patience with me along the way. I couldn’t have done this without you and your team.

I would like to thank the support staff who worked on this project, including everything from the construction of the high tunnels to the collection of scientific data this includes the Absaraka team, Collin Auwarter and Jacob Kluza and additional support staff. I would like to specifically thank Rojee Chipula Pradhan for her help with collecting, inputting and organizing the data. Her dedication to her work can be seen by her steadfast and determined spirit, her keen observations in the field, and her beautiful smile.

And finally, thank you to my family, Mom, Jason and Trevor, for allowing me to pursue this dream. And thank you to my son, Daniel, for giving me something to look forward to each day- unending joy in my heart and a smile on my face. My hope for you is that you will always know how much you are loved, always pursue your dreams, and never give up.

The excess produce from these trials was donated to local food banks in both Cass and Williams Counties.

DEDICATION

I dedicate this paper to my late father, Dan Hieb. There isn't a day that goes by since your passing that I don't think about you and appreciate the values, hard work and perseverance you instilled in Trevor and me.

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LIST OF ABBREVIATIONS

ABS .... Absaraka

CMV .... Cucumber Mosaic Virus

FD .... Field

HT .... High Tunnel

NDAES .... North Dakota Agricultural Experiment Station

NDAWN .... North Dakota Agricultural Weather Network

NGP .... Northern Great Plains

NV .... Nesson Valley

RH .... Relative Humidity

ToMV .... Tobacco Mosaic Virus

TMV .... Tomato Mosaic Virus

TSSM .... Two-Spotted Spider Mite

USDA .... United States Department of Agriculture

WREC .... Williston Research Extension Center

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CHAPTER 1: INTRODUCTION

Historically, commercial vegetable growers have used some form of environment modification technique, whether to increase plant growth and performance, lengthen the growing season or protect from pests (Jones and Emsweller, 1931). Traditionally, warm-season vegetables were started early in cold frames, hotbeds or greenhouses to be transplanted to an outdoor field at a later date. The concept of vegetable forcing is still relevant in today's vegetable industry with the use of greenhouses, low tunnels and high tunnels. High tunnels, at their most basic, consist of a rigid frame and a plastic film covering (Carey et al., 2009). High tunnels allow for an extended growing season both in the spring and fall; crop protection from natural weather events such as wind, hail and heavy rain; improved crop yield and quality; as well as improved disease and pest management (Blomgren and Frisch, 2007; Carey et al., 2009; Knewtson et al., 2010). In temperate regions, the primary use for high tunnels is season extension by modifying the environment. Horticultural crops grown under protected cultivation worldwide continue to grow, and will continue to have a positive influence on locally grown, fresh-market produce. (Lamont, 2009).

High tunnels effectively modify the growing environment to extend the growing season in cold climates of the northern Great Plains (Knewtson et al., 2010). High tunnels alter the growing environment by passively trapping solar energy, thereby increasing air and soil temperatures, as well as relative humidity. This modified environment is advantageous for high-value, warm-season crops such as tomato (*Solanum lycopersicum* L.), pepper (*Capsicum annuum* L.), and cucumber (*Cucumis sativus* L.). In a three-year study on tomato cultivars grown under high tunnel production in northern New England, cultivar performance as well as grower considerations were assessed (Warren, 2015). The study, conducted from 2011 to 2013, found an overall decline in plant yields, possibly due to increased pathogen pressures as well as nutrient depletion of the soil. However, the study did identify ‘Geronimo’ as consistently producing the highest marketable yields across all years. Other studies, conducted at Pennsylvania State University on high tunnel cucumbers showed higher marketable yields with the use of trellising that resulted in straighter, more uniform fruit (Bogash, 2014). High tunnels have been shown to extend the season, improve crop quality, increase production, and positively influence local markets in the neighboring state of Minnesota (Nennich, 2012). There is no published research on high tunnel production in North Dakota.

Literature Review

High tunnels, also known as hoop houses, are fundamentally different than greenhouses. Greenhouses are permanent structures that utilize not only the sun’s radiation as a source of heat, but also require electricity to employ fully automated heating and ventilation systems (Lamont, 2009). High tunnels can be constructed out of metal or wood framing, with rigid poly, plastic or glass end walls, and either an arched or peaked roof style that is covered in plastic. The growing environment in a greenhouse is much more controlled than in a high tunnel. Crops grown in a greenhouse are not planted directly into the ground as they are in high tunnels, but are grown in containers on above-ground shelving and/or suspended from the structural components of the roof as a means of space utilization.

In 1999, worldwide cultivation of horticultural crops grown under greenhouse or plastic house production was estimated to be 800,000 ha (Knewtson et al., 2010). Worldwide high tunnel production varies widely depending on climatic conditions. In tropical regions, protection from rainy season monsoons and wind damage is the main reason high tunnels are used. In temperate regions, high tunnel use is for season extension by modifying the environment. High tunnel crop production is included in a broader category known as “protected cultivation,” and therefore more accurate numbers worldwide are hard to come by. However, regardless of category, horticultural crops grown under protected cultivation worldwide continue to grow, and will continue to have a positive influence on locally grown, fresh-market produce. (Lamont, 2009).

An informal national survey was conducted in 2007 to gain insight into the use of high tunnels across the United States (Carey et al., 2009). Forty-six states responded, including North Dakota, which reported less than one acre of estimated area under high tunnel production, and an estimated number of 6 high tunnels in the state. At the time of the survey, North Dakota had no research or demonstration work using high tunnels.

The 2012 USDA-NASS census cited 26 farms in the state that grew vegetables under glass or other protection (USDA-NASS, 2014). Still, the difference between high tunnel and greenhouse remains to be distinguished in this report. More recently, however, the Natural Resources Conservation Service (NRCS) Resource Conservationist, Tracy Dove has stated that in North Dakota, the NRCS has assisted in the implementation of 115 high tunnels to date (personal correspondence, December 11, 2017).

Vegetable Crops

Tomato. The number one crop grown under high tunnel production worldwide is tomato (Carey et al., 2009; Knewtson et al., 2010; Lamont, 2009). Other crops of importance include those in the Cucurbitaceae and Brassicaceae families. Because of their adaptability to trellising techniques, indeterminate tomato cultivars can be pruned and trained vertically to maximize the space within a greenhouse or high tunnel (Wittwer and Castilla, 1995). Tomatoes in protected culture also produce fruit much earlier than field grown because of increased temperatures, which results in higher economic return due to a longer harvest season (Rogers and Wszelaki, 2012). Tomatoes grown in high tunnels have greater quality and marketability due to protection from hazardous environmental conditions such as wind and hail, as well as biotic factors such as birds, insects and rodents (Rogers and Wszelaki, 2012; Carey et al., 2009).

Tomatoes originated along the coastal regions of Ecuador and Peru, as well as northern Chile (Welbaum, 2015). The fruit was slow to gain popularity in North America largely due to the myth that it was poisonous because of its association with deadly nightshade (*Atropa belladonna* L.). The first mention of tomato cultivation in the United States was by Thomas Jefferson in 1781 (Jones and Emsweller, 1931). The tomato industry grew rapidly in the late 19th and early 20th centuries and is currently grown in almost all parts of the United States. It is a staple in home gardens and at farmer's markets. Tomato is typically grown commercially in both the field and greenhouse for fresh market and for processing into products such as juice, purees or whole pack (Decoteau, 2000).

Tomatoes are high in nutrition and low in calories. One medium tomato (148 g) contains 40% of the daily recommended intake of Vitamin C based on a 2,000 calorie diet (Decoteau, 2000). Besides Vitamin C, tomatoes are also a good source of Vitamins E, K, B1, B3 and B6 as well as beneficial phytochemicals like β-carotene, lutein, zeaxanthin and lycopene (Welbaum, 2015). Over the last 20 years, health officials have recommended a diet full of whole grains, fresh vegetables, lean meats, low-fat dairy, and limited amounts of sodium, saturated and trans-fats and added sugars. The health benefits associated with a diet full of fresh vegetables has almost doubled the US per capita consumption of tomatoes since the 1980s (Welbaum, 2015).

Cucumber. Cucumbers belong to the Cucurbitaceae family, and have been cultivated for thousands of years (Welbaum, 2015). India is believed to be the center of origin, with the North

American introduction by the Colonists occurring in the 16th century. Today, US commercial cucumber production occurs along the east coast from New York to Florida, as well as California, Ohio, Michigan, Wisconsin and Texas with 50,000 ha nationally harvested in 2017 (USDA/NASS, 2019). Cucumbers are the fourth most important crop cultivated worldwide behind tomato, cole crops and onion with a total world production of 1,958,000 ha in 2011 (Welbaum, 2015).

Cucumbers are a low-calorie vegetable composed mainly of water (Welbaum, 2015). Nutritionally, cucumbers do not contain high values of vitamins, fiber, carbohydrates or protein like other vegetables, but they are an excellent source of minerals such as potassium and other phytochemicals. Because cucumbers are low in calories, they are a popular addition to salads and side dishes. Recently, the "cocktail cuke" and mini cucumbers, which are the results of crosses between long and short European types have garnered consumer demand because of their snack-like appeal, thin skins and crunchier texture (Mefferd, 2017).

Peppers. Peppers are commonly found in the tropics and subtropics of South America, and have been cultivated for centuries (Welbaum, 2015). It is thought that Columbus was responsible for their introduction into Europe where their cultivation as a food crop quickly moved throughout the world. Peppers have a long history of medicinal uses in many folk cultures most likely due to their antimicrobial properties. In recent times, nearly 42,000 acres of bell peppers are produced in the United States (USDA, 2019).

Pepper fruits are anti-climacteric unlike the tomato, which means that they do not continue to ripen after harvest even if exposed to ethylene (Welbaum, 2015). They are an excellent source of Vitamin A, and as the fruit ripens, the levels of Vitamin A increase dramatically. Pepper fruits are susceptible to harvest damage because they lack an abscission area on the fruit pedicel thus, care must be taken when harvesting to avoid damaging the surrounding branches and leaves.

Cultivar Trials. Vegetable cultivar trials are important to producers because they give comparative information on many important performance traits (Warren et al., 2015). Traits such as marketable yield, total number of fruit produced, the percent of unmarketable fruit, consumer preferences, and susceptibility to diseases and insects are all critical components that producers evaluate when choosing a cultivar. This information is important for producers deciding whether or not higher yields are better than a cultivar that produces fewer, but consistently marketable fruit. Furthermore, cultivar performance can vary greatly from one region or state to another, making the decision of which cultivars to grow and how a cultivar will perform on their farms all the more difficult for producers (Sanchez et al., 2011).

Pests

Tomatoes are susceptible to many economically important diseases including, *Tobacco Mosaic Virus* (TMV) and *Tomato Mosaic Virus* (ToMV) (Jones et al., 2014). Both viruses affect plants in the Solanaceae family which includes tomato and pepper. Because they are closely related, these viruses are discussed collectively in the literature. Symptoms of both viruses are highly variable depending on virus strain, plant cultivar, time of infection, light intensity and temperature, and can include things like distorted fern-like leaves, reduced fruit set, uneven fruit ripening and mosaic patterns on the foliage (Koike et al., 2007; Jones et al., 2014). Both viruses also have no known insect vector, but are mechanically transmitted through human activities such as pruning and handling. Of the two, ToMV is seedborne, and a treatment of trisodium phosphate or heat may remove any external and possibly internal virus (Jones et al., 2014).

Management of these particular viruses is fairly straightforward. Because their transmission occurs during human-related activities, sanitation is key (Jones et al., 2014). Washing hands with soap and water, sanitizing pruning shears and equipment, removing leaf and root debris as well as treating seeds before planting and utilizing resistant cultivars can help reduce the spread of ToMV and TMV. Once established, ToMV is a hardy virus and can survive in harsh conditions for extended periods of time. Depending on the moisture present, the virus can persist in soil, leaf and root debris for years.

Cucumber mosaic virus (CMV) is distributed worldwide and can infect over 1,200 vegetable species including tomato, pepper and cucumber (Jones et al., 2014). Host range also includes many ornamental plant species, as well as numerous weeds. Infection with CMV causes highly characteristic symptoms on tomato which are described as filiformity where the leaf blades are deformed in a ”strap-leaf” or ‘shoe-string’ like manner, and the plants are bushy and stunted (Koike et al., 2007). Symptom expression in all three plant species is highly dependent upon several factors: strain of virus, plant stage at the time of infection, and growing conditions such as field or greenhouse.

In pepper and cucumber, CMV is seedborne (Zitter et al., 1998). Cultivar resistance is reported in cucumber. There are no resistant cultivars in tomato, and the virus is not carried in the seed. In all three plant species, however, it can be insect vectored. There are over 75 species of aphids that can transmit CMV, one of which is the green peach aphid (*Myzus persicae* (Sulzer)) (Jones et al., 2014). With their piercing-sucking mouthparts and global distribution, green peach aphid is an economically important pest that affects over 800 plant species, and can vector over 100 plant diseases (Capinera, 2001). Management of CMV includes scouting for aphids and keeping aphid populations low to delay infestation on young plants. Isolating the desirable crop, using a physical barrier or a taller non-susceptible crop may delay initial infection. Managing weeds that harbor CMV can be difficult due to its extensive host range, but steps should be taken to reduce virus pressure by eradicating weeds nearby (Jones et al., 2014).

Because of the sheltered environment created under high tunnels, insect populations as well as disease incidence have a tendency of increasing quickly (Ingwell et al., 2017). As noted previously, the green peach aphid is considered an important high tunnel pest. Aphids are small, soft bodied, pear-shaped insects having six legs, two antennae and two cornicles extruding from the rear part of the body (Pedigo, 2009). They appear in both winged and un-winged forms and most species have complex life cycles. Aphids damage crops in three important ways: 1) feeding by sucking the sap (plant juices) from plant cells, thereby interfering with normal plant functions; 2) producing substantial amounts of excrement known as "honeydew," which becomes a substrate for sooty mold on leaf surfaces and fruit, degrading fruit quality and reducing photosynthesis; and 3) serving as vectors of many plant diseases (Flint, 2013; Zitter et al., 1998).

Another arthropod pest commonly found in high tunnel environments is the two-spotted spider mite (TSSM) (*Tetranychus urticae* Koch). Belonging to the arachnid family, TSSM are small 0.3-0.5 mm long, soft bodied pests that can go undetected on the undersides of the leaves (Godfrey, 2011; Jones et al., 2014). They live up to their name, having two dark spots on either side of their abdomen and silk glands at the rear enabling them to create extensive webbing all over the plant tissue. This webbing also helps protect them at all life stages against predators and insecticides.

In the case of both aphids and spider-mites, temperature plays a crucial role in development. Spider mite population is favored by hot, dry conditions, going from egg to adult in as little as 5 days (Jones et al., 2014). Aphids can also rapidly reach maturity due to favorable temperatures, days or less, however; they have the ability of reproducing both sexually and asexually (parthenogenesis).

Scouting for these pests should be done on a weekly, if not daily basis. Due to the reproductive nature of these insect pests, as well as the conducive environment, management techniques should have a multi-faceted approach; biological cultural and chemical. For example, biological control could include the use of beneficial predator insects, and cultural control could include the use of reflective mulches. Chemical treatment thresholds for both green peach aphid and spider mites in cucumber, pepper and tomato are not well defined (Aegerter et al., 2013; Stoddard et al., 2009; and Smith et al., 2009). In potato, thresholds are set at 10 aphids/leaf in well-rotated fields planted with certified seed; in poorly managed fields of uncertified seed, 1 aphid/leaf is acceptable (Kabaluk et al., 2006). In soybean, thresholds for two-spotted spider mite are monitored based on the infestation of the overall plant, starting at the base and working its way up into the canopy (Ostlie and Potter, 2013). The spray threshold is when the mites are found in the middle canopy, with economic loss occurring when the mites and stippling damage are found in the upper canopy.

In terms of efficacy, insecticides and miticides with the same mode of action that are used repeatedly often lead to the development of resistance. Using more than one mode of action is recommended, especially for aphids, and care should be taken when applying insecticides in an enclosed environment. Predator insect populations also should be taken into account while scouting for pests. Most insecticides are non-selective and will have a negative effect on beneficial insects as well as insect pests.

Research Objectives

The objectives of this project were to evaluate nine cultivars each of three traditional warm-season crop species: tomato, pepper, and cucumber; and to compare crop yield and quality in western and eastern North Dakota when these crops are grown inside and outside a high tunnel.

CHAPTER 2: TOMATO

Introduction

Tomato (*Solanum lycopersicum* L.), belongs to the Solanaceae or nightshade family, and is one of the most widely cultivated species in this family behind the potato (Welbaum, 2015). Tomato is the number one crop grown in high tunnels, and considered one of the most profitable crops for a market grower (Carey et al., 2009; Knewtson et al., 2010; Lamont, 2009). Unfortunately, there has been no published research on high tunnel tomato production in the state.

The economic importance of tomato worldwide was valued over $58 billion (US dollars) in 2011, and ranked eighth as the most valuable agricultural commodity (Welbaum, 2015). Increased consumer demand for fresh tomatoes, centralized large-scale vegetable farms, advances in perishable product transportation and fuel efficiency, and improvements in plant breeding have all played a role in year-round tomato availability (Mefferd, 2017). However, this year-round availability came at the cost of product flavor, specifically, the flawless, flavorless grocery store tomato that most consumers are familiar with today. Recently, there has been an increase in consumer awareness of the importance of local food systems. Consumers want safe, economical, and sustainable food markets that provide produce free from foodborne illnesses and contamination, and flavorful and nutritious produce that is locally grown.

The movement for locally grown produce nationwide can be seen by the number of farmers markets appearing in each state. The United States Department of Agriculture National Farmers Market Directory (2018) has over 8,600 registered farmers markets across the nation. Though North Dakota has been largely recognized for its agricultural commodities, it is no stranger to the demand for local foods. There are over 50 farmers markets across the state with more than 125 producers contributing to local markets (J. Good, personal correspondence, December 20, 2018). This, along with a current population increase of up to 12.3% since the 2010 United States Census, will continue to be the driving force for more local vegetable growers. The high economic value, consumer local food movement, as well as the consistency and predictability of crop quality will continue to drive production of high tunnel tomatoes.

In a three-year study on tomato cultivars grown under high tunnel production in northern New England, cultivar performance as well as grower considerations were assessed (Warren, 2015). The study, conducted from 2011 to 2013, found an overall decline in plant yields, possibly due to increased pathogen pressures as well as nutrient reduction of the soil. However, the study did name the cultivar, Geronimo, as consistently producing the highest marketable yields across all years. A field study conducted at Purdue’s Meigs Horticulture Research Farm south of Lafayette, IN in 2011 and 2012 focused on identifying three key organic tomato production components: well adapted tomato cultivars to the U.S. Midwest; cultivars that perform competitively under organic production; and those that possess the desired quality characteristics by the consumer such as flavor or texture (Hoagland et al., 2015). The study identified the hybrid cultivar, Mountain Magic, among others as a top performer for Midwest organic tomato production.

High tunnels have been shown to extend the season, improve crop quality, increase production, and positively influence local markets in other states such as Minnesota (Nennich, 2012). Unfortunately, there is a lack of published research on high tunnel production in North Dakota. In addition, there is limited information on high tunnel production from other states with comparable climates. North Dakota’s climate is heavily influenced by its location as the geographic center of North America within the Northern Great Plains (NGP), and is characterized by widespread fluctuations in temperature (Enz, 2003). High tunnels are semi-permanent structures covered in plastic that help mediate drastic temperature fluctuations by passively heating the air, plants and soil underneath the plastic; subsequently warming the air faster than it can escape and thereby increasing nighttime temperatures.

The objectives of this trial were to evaluate nine commercially available tomato cultivars at two locations representing eastern and western North Dakota to be conducted as side-by-side trials of outdoor field and indoor high tunnel production.

Methods and Materials

Site Description. The experiment was conducted in the 2016 and 2017 growing seasons at two separate locations in North Dakota representing the east and west climatic regions of the state. Within the NGP, the state of North Dakota falls within three distinct ecological sub-regions or ecoregions which are defined by Omernick (1987) as the Northwestern Great Plains, Northwestern Glaciated Plains and Northern Glaciated Plains. Of those three ecoregions, the trial locations are representative of the climatic conditions of the Northwestern Glaciated Plains (western) and the Northern Glaciated Plains (eastern) regions.

The western location was at the NDSU Williston Research Extension Center (WREC) Nesson Valley Irrigation Research and Development Project (48°09’44.1” N and 103°06’29.7” W) near Williston, ND in Williams County (“NV”). This region is characterized by a semiarid climate with low humidity, frequent drying winds, low rainfall, abundant sunshine, hot summers and cold winters (Tollerud et al., 2018). Annual average precipitation is approximately 250 mm.

The eastern location was at the NDSU Dale E. Herman Research and Arboretum farm (46°59’28” N and 97°21’20” W) near Absaraka, ND (“ABS”) in Cass County. This region is characterized as continental, that is hot or warm summers and cold winters with an average annual precipitation range between 380 and 760 mm (Tollerud et al., 2018). The total rainfall, daily maximum, and minimum air temperatures from May to September were recorded by North Dakota Agricultural Weather Network (NDAWN) for the two locations and years can be found in Appendix Figures A.3 and A.4.

Additional information on each location, high tunnel size and soil classification can be found in Appendix Table A.1. One high tunnel was constructed at each site in the fall of 2015 and completed in the spring of 2016. Both high tunnels (Northpoint, Rimol Greenhouse Systems, Inc. Hooksett, NH) were built in a north-south orientation with 13-gauge steel framework; double air inflated 4 year-rated 6 mil clear polyethylene greenhouse film treated with anti-condensate and ultraviolet features; and nominal lumber-framed end walls, baseboards and hip boards. Ventilation was accomplished by thermostatically controlled electric roll up sidewalls running the lengths of both sides set to open at 27 °C, and motorized shutter vents in each gable end wall set to open at 21 °C. Sidewalls were manually closed during high wind and storm events when deemed necessary.

Site Preparation. Prior to planting, each location collected soil cores to a depth of 30 cm and submitted them to the NDSU Soils Testing Lab (Fargo, ND) for a basic soil nutrient test (Appendix Table A.2.). The 2014 Midwest Vegetable Production Guide (Engel et al., 2014) was used for determining nutrient recommendations of N-P-K. A split application of N applied pre-plant, broadcasting granular 46% Urea fertilizer and incorporating it into soil, and the rest of the N was applied during the growing season as fruit development began. The post-planting fertilizer application used liquid 28% UAN injected into the irrigation system and applied to drip-irrigated tomatoes. Prior to planting, beds were tilled and formed using rotor-tiller equipment. All plantings were in single rows with one line of 15-mil drip tape (Toro® Aqua-Traxx, DripWorks, Willits, CA) with emitters spaced 20.3 cm on center with a 2.15 x 10^{-4} m^3/s flow rate that were installed after transplanting. The irrigation from planting until the end of June was scheduled on Monday, Wednesday and Friday. At the beginning of July, irrigation was reduced to twice a week for 5 hours. Weed management was accomplished using a 15-year, 3 oz. woven weed barrier (Agriculture Solutions, Strong, ME) laid on either side of the row and hand labor as needed.

Temperature. Weather data and soil temperatures were monitored in the field using the North Dakota Agricultural Weather Network (NDAWN). The NV location used the Hofflund Station located at 590 m elevation. The ABS location used the Prosper Station with an elevation of 284 m above sea level. The NDAWN station temperature and relative humidity sensors were set at 1.5 m from the soil surface. Soil temperature readings were taken at a depth of 10 cm for bare soil. A WatchDog 1000 series micro station (Spectrum Technologies, Inc. Aurora, IL) was used at the NV high tunnel to monitor air temperature, relative humidity and soil temperatures. A Decagon EM50 data logger (Decagon Devices, Inc., Pullman, WA) was set up at ABS to monitor inside and outside air temperature readings. Both data loggers were set up to be comparable to the NDAWN stations for air temperature.

Plant Materials. The high tunnels used for this trial also housed independent pepper, cucumber, and cut flower cultivar trials occurring simultaneously for a total area of 232 m^2 under protection. For the indoor high tunnel (HT) and the outdoor field (FD) trials, nine indeterminate slicing tomato cultivars were selected (Johnny's Selected Seeds Winslow, ME). Cultivar names, disease resistance codes, production type, average fruit weight and days to maturity are presented in Table 2.1. Due to the discontinuation of the cultivar, Trust, in 2017, the cultivar, Chef's Choice Orange, was substituted in its place. These cultivars were removed from the statistical analysis in order to combine years. Consideration was given to cultivars that were recommended by Johnny's Selected Seed catalog (2016) for either protected culture production, that is either high tunnel or greenhouse, or those suited to field production or field culture. Eight of the cultivars were F1 hybrids and one was open pollinated. Most of the cultivars selected were widely adapted cultivars including the field recommended cultivars, New Girl and Best Boy, the Japanese-style, greenhouse cultivar Tomimaru Muchoo, and the open-pollinated, heirloom-type cultivar Pink Berkeley Tie Dye.

Table 2.1. Tomato trial cultivars, seed source and days to maturity according to Johnny's Selected Seed (2016).

Cultivar name	Disease resistance[y]	Production type[x]	Average fruit weight in grams	Days to maturity[w]
Arbason F_1[z]	F2, TMV, V	PC	227	76
Best Boy F_1	V, F2, N, AS, L	FC	227	75
Bigdena F_1	F2, FOR, LM, TMV, ToMV, V	PC	312	77
Cobra F_1	F2, TMV, V, L	PC	198	72
New Girl F_1	F2, V	FC	142	62
Pink Berkeley Tie Dye	N/A	FC	283	70
Pink Wonder F_1	F2, LM, ToMV, V	PC	227	73
Tomimaru Muchoo F_1	F2, FOR, LM, ToMV.	PC	198	72

[z] Refers to F_1 hybrid.

[y] AS=Alternaria Stem Canker, F2=Fusarium Wilt (Races 1&2), FOR=Fusarium Crown and Root Rot, L=Gray Leaf Spot, LM=Leaf Mold, N=Nematodes, TMV=Tobaco Mosaic Virus, ToMV=Tomato Mosaic Virus, V=Verticillium Wilt.

[x] Production type FC = Field Culture and PC = Protected Culture.

[w] Days to maturity is the days from transplant to first harvestable fruit.

Transplant Establishment. In 2016, tomato seeds were started in the North Dakota Agricultural Experiment Station (NDAES) greenhouses in Fargo, ND (20 ± 2°C, 16:8 L:D, RH = 40-65%) in 606-deep cell packs (T.O. Plastics, Clearwater, MN) filled with a growing medium (PRO-MIX FLX, Premier Horticulture Inc., Quakertown, PA) and transplanted at 4 weeks into SVD-450 molded plastic pots (T.O. Plastics, Clearwater, MN) filled with the same growing medium. Plants were not fertilized but watered with tap water once a week (100 mL). Half of the seedlings were transported to NV location and the other half were taken to the ABS location after

8 weeks of development. The timing of the high tunnel construction extended beyond the anticipated planting date, resulting in more mature seedlings at the time of transplanting on 25 May at both locations for the high tunnel and field trials.

In 2017, seedlings for the ABS location were started in the NDAES greenhouse while seedlings for the NV location were started at WREC under indoor fluorescent lighting (40W Gro-Lux Wide Spectrum, Sylvania Ontario, Canada). In an effort to reduce seed borne viruses, the seeds at both locations were treated with a 10% solution of trisodium phosphate TSP (Savogran Company, Norwood, MA) for 15 min. and rinsed in cold water. The seeds were then air-dried overnight and seeded the next day into the same growing medium previously identified. At four weeks, the seedlings were transplanted at both locations on 3 and 11 May at ABS and NV, respectively in the high tunnels, and on 15 and 26 May at ABS and NV, respectively for the field. At both locations and years, the transplants were spaced at 91 cm centers within the row and a 91 cm spacing between rows. At ABS, the extra 1.2 m high tunnel width allowed for two plants per plot, which were pruned and trained to one leader that was suspended from the high tunnel rafters using tomahooks (Van den Wijngaart, The Netherlands) at the NV location and Rollerhooks® (Paskal Technologies Agriculture, Israel) at the ABS location.

Data Collection. Fruit harvest took place twice a week at both locations for approximately 14 and 9 weeks in HT and FD, respectively, using the tomato ripeness unofficial visual aid from the USDA Marketing Service Fruit and Vegetable Division and the United Fresh Fruit and Vegetable Association to determine ripeness (USDA, 1975). The marketability evaluation was conducted only at the NV location due to the subjective nature of the data collection. Fruit quality and marketability was determined based on the USDA vegetable grading standards for greenhouse tomatoes which consists of U.S. No.1 (highest quality) and U.S. No. 2

marketing grades (USDA, 2007). The quality standards are based on shape, size, color, freshness, and surface defects. Tomatoes were considered unmarketable if they were deeply bruised, rotten, cracked with mold, or had defects that would otherwise affect postharvest storage of the fruit. Fruits with minor cosmetic cracks or scars were considered marketable. The percentage of marketable tomatoes was calculated as the number of marketable tomatoes divided by the total number of harvested tomatoes, multiplied by 100.

The average yields in kilograms per plant were based on harvest weights collected. Average number of fruit were based on the total fruit harvested from each plant throughout the growing season. Average fruit weights were calculated as the total yield divided by the total number of fruit harvested. Yields and total fruits from inside the high tunnel were compared to those grown in the field trials, but were not statistically analyzed together. The percent of marketable fruit were calculated as the difference between marketable and unmarketable fruit divided by the total and converted to a percentage.

In 2016 at NV, observations were recorded of leaf filiformity, plant stunting, and a chlorosis on some of the tomato plants in late June. The symptoms evoked initial suspicion of herbicide carryover from the site's previous use as a five-year switch grass study. It was unclear whether the symptoms were disease-related at the time. However, all plants were pruned without the proper sanitation methods (Pategas et al., 1989). In 2017, the symptom expression was noted on more than 50% of the tomato plants by late June and tissue samples were sent to the NDSU Plant Diagnostic Lab in Fargo, ND, which were confirmed for *Tobacco Mosaic Virus* (TMV), *Cucumber Mosaic Virus* (CMV) and *Tomato Mosaic Virus* (ToMV). It was necessary to remove all tomato plants to prevent inoculum from spreading and persisting; subsequently abandoning the trial.

Experimental Design and Statistical Analysis

The trials were planted in a randomized complete block design with four replications. The weight, number of fruit and average fruit size data collected for the cultivars Trust in 2016 and Chef's Choice Orange in 2017 were taken out of the statistical analysis in order to run the years together. The statistical analysis of data were performed using a linear model for SAS 9.4 (PROC GLIMMIX with the REML estimation method, SAS Institute, SAS Circle, Cary, NC) where cultivar and environments were considered fixed, and replications within environment were considered random effects. An environment was considered one experiment conducted at a specific location and a specific year. Mean separation was done through the PDIFF function standard error for a least significant difference calculation using Tukey's honestly significant difference pairwise comparison test. An alpha level of $p < 0.05$ was used for all hypothesis tests. The mean separation for the marketability analysis conducted only at the NV location. Homogeneity of variance was tested in marketability analysis using Levene's test.

Results and Discussion

High tunnel trial. The 2017 NV trial was abandoned due to severe disease incidence and plant mortality among all replications in the trial. Only three environments were used in the statistical analysis ABS 16, NV 16 and ABS 17 (Appendix Table A.3). Traits of interest collected were yield as total fruit weight per plant in kg, total number of fruit harvested per plant, and average fruit weight calculated as the total fruit weight divided by the total number of fruit harvested expressed in grams.

The main effects of environment and cultivar were significant for average number of fruit per plant. Cultivar by environment interactions occurred for average yield per plant and average fruit weight (Appendix Table 1.3). When the cultivar by environment interaction is sliced into cultivar-specific components for yield, the resulting p-values indicate the cultivars Bigdena, New Girl, Pink Berkeley Tie Dye and Tomimaru Muchoo showed no difference over the three experiments, all other cultivars performed differently in at least one environment (Table 2.2). In the environment-specific tests, p-values indicate a significant cultivar response in only NV 16.

Table 2.2. P-values for slices of the cultivar by environment interaction for the main effect average yield per plant for the high tunnel tomato trial conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar-specific tests		Environment-specific tests	
Cultivar	P-value[y]	Location, Year	P-value[z]
Arbason	0.0033	Absaraka, 2016	0.2212
Best Boy	0.0004	Nesson Valley, 2016	0.0022
Bigdena	0.0672	Absaraka, 2017	0.0881
Cobra	0.004		
New Girl	0.0789		
Pink Berkeley Tie Dye	0.2826		
Pink Wonder	0.0248		
Tomimaru Muchoo	0.3131		

[y] Each cultivar specific test compares the average responses of a cultivar across three environments; each test has 2 numerator degrees of freedom.
[z] Each environment-specific test compares the average response of eight cultivars in the specified environment; each test has seven numerator degrees of freedom.

When sorted by environment, the cultivar Cobra produced the greatest average yield per plant in ABS 16, but not significantly more than ‘Arbason’, ‘Best Boy’, ‘Bigdena’, ‘New Girl’ and ‘Pink Wonder’ (Table 2.3). In 2017, ‘Tomimaru Muchoo’ produced the greatest yield at NV, but was not significantly different than ‘Bigdena’, ‘Cobra’ and ‘New Girl’. At ABS 17, ‘Pink Wonder’ and ‘Arbason’ produced the greatest yield although ‘Arbason’ was not significantly different than ‘Tomimaru Muchoo’. The average yields per plant tended to be higher in ABS 16. Even though 2016 seedlings were twice as old when transplanted into the high tunnel, total yield/plant was expected to increase in 2017, as plants were transplanted 21 days earlier at ABS and 14 days earlier at NV. However, this was not the case. Disease incidence was present in NV16 and ABS17.

Table 2.3. Average yield per cultivar harvested from the high tunnel trials at Absaraka and Nesson Valley, ND in 2016 and 2017.

Cultivar	ABS 16[z]		NV 16		ABS 17	
	----------------------- kg/plant ------------------------					
Arbason	6.9	ab[y]	2.6	bc	5.2	ab
Best Boy	6.4	ab	1.6	c	2.4	e
Bigdena	6.2	abc	4.6	ab	3.3	cde
Cobra	7.6	a	4.6	ab	3.4	cd
New Girl	6.5	ab	4.6	ab	3.7	cd
Pink Berkeley Tie Dye	4.7	c	2.8	bc	3.2	de
Pink Wonder	6.9	ab	3.5	bc	5.4	a
Tomimaru Muchoo	5.6	bc	6.1	a	4.3	bc

[z] ABS16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017.
[y]Within a column, means followed by the same letters are not significantly different at P<0.05 using Tukey's honestly significant difference test (n=4).

With respect to average number of fruit, the cultivar New Girl produced the most fruit/plant at 46/plant but was not significantly different than Tomimaru Muchoo (Table 2.4). While 'Pink Berkeley Tie Dye' produced the fewest at just 17/plant, it was not statistically different than Best Boy or Bigdena. The ABS 16 environment produced significantly more fruit per plant as compared to NV 16 and ABS 17.

Table 2.4. Influence of the main effects of environment and cultivar on average number of tomato fruits harvested per plant for high tunnel tomato trial conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar	Avg. No./plant	Environment	Avg. No./environment
Arbason	32 bc[z]	ABS 16[y]	51 a
Best Boy	23 de	NV 16	16 b
Bigdena	22 de	ABS 17	21 b
Cobra	31 c		
New Girl	46 a		
Pink Berkeley Tie Dye	17 e		
Pink Wonder	25 cd		
Tomimaru Muchoo	38 a		

[z]Within a column, means followed by the same letters are not significantly different at P<0.05 using Tukey's honestly significant difference test (n=4).
[y]ABS16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017.

When the cultivar by environment interaction for average fruit weight is sliced, the resulting p-values indicate the cultivars Bigdena, Cobra, Pink Berkeley Tie Dye and Tomimaru

Muchoo to have performed differently in at least one environment. When the interaction is sliced by environment, the p-values indicate a significant cultivar response to all environments except ABS 16 (Table 2.5).

Table 2.5. P-values for slices of the cultivar by environment interaction for main effect average fruit weight per plant for high tunnel tomato trial conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar-specific tests		Environment-specific tests	
Cultivar	P-value[y]	Location, Year	P-value[z]
Arbason	0.4653	Absaraka, 2016	0.4001
Best Boy	0.1913	Nesson Valley, 2016	<.0001
Bigdena	<.0001	Absaraka, 2017	0.0007
Cobra	0.0093		
New Girl	0.1042		
Pink Berkeley Tie Dye	<.0001		
Pink Wonder	0.0936		
Tomimaru Muchoo	0.0074		

[y] Each cultivar specific test compares the average responses of a cultivar across three environments; each test has 2 numerator degrees of freedom.
[z] Each environment-specific test compares the average response of eight cultivars in the specified environment; each test has seven numerator degrees of freedom.

When the data is sorted by experiment, the average fruit weight tend to be higher at NV (Table 2.6). The trend from ABS 16 to ABS 17 showed an increase in average fruit weight despite the decline in total yield. The cultivars that produced the fewest fruit/plant, Bigdena and Pink Berkeley Tie Dye, produced the largest fruit size at 427 g and 470 g, respectively at NV16. The smallest fruit size at 85 g was 'New Girl' at ABS 16.

Table 2.6. Average fruit weight harvested per cultivar in high tunnel trials conducted at Absaraka and Nesson Valley, ND in 2016 and 2017.

	ABS 16[z]	NV 16	ABS 17
Cultivar	------------------------ fruit weight (g)		-------------------------
Arbason	134 c[y]	177 b	173 de
Best Boy	133 c	187 b	199 cd
Bigdena	140 bc	427 a	285 a
Cobra	132 c	253 b	188 d
New Girl	85 d	167 b	116 f
Pink Berkeley Tie Dye	156 ab	470 a	247 b
Pink Wonder	168 a	247 b	232 bc
Tomimaru Muchoo	96 d	219 b	150 ef

[z] ABS16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017.
[y] Within a column, means followed by the same letters are not significantly different at P<0.05 using Tukey's honestly significant difference test (n=4).

While not marketed as a protected culture cultivar, New Girl produced the most average fruit per plant harvested from the high tunnel followed by ‘Tomimaru Muchoo’ which is a recommended greenhouse tomato. The cultivar New Girl was also expected to have the earliest days to maturity (62 days) and smaller average fruit size (142 grams) giving it a potential advantage over others (Johnny’s Selected Seed, 2016). Some tomato cultivars are better suited to increased fruit production over others which may prove beneficial for producers when sold by the individual fruit rather than by weight.

The results found in this study are similar to those found by researchers in Durham, NH in which 15 indeterminate cultivars were tested in a high tunnel from 2011 to 2013. Among their selected cultivars was Arbason which had similar mean fruit number per plant (31) compared to this study (32) averaged over three experiments. The trial also included the cultivar Cobra which was similar in overall average fruit weight (205g) compared to this trial (191g). The researchers noted an overall decline in production citing reasons having to do with nutrient depletion of the soil and increased pathogen pressure within the high tunnel environment (Warren, Sideman and Smith, 2015).

The marketability analysis showed that while only statistically different than two other cultivars, Arbason produced the most marketable fruit at 99% (Figure 2.1). The cultivar with the lowest marketability at 34% was Pink Berkeley Tie Dye, the only open pollinated cultivar described by the seed source as having “soft” fruit and no disease resistance. The second lowest marketable cultivar, Pink Wonder was described as having soft flesh and thin skin prone to cracking under uneven watering conditions. Though not much statistical differences were found (P=0.0072), the cultivars Cobra and Arbason produced marketable yields at 85% and 99%, respectively which corresponded to what researchers Warren, Sideman and Smith found in their variety trial in New Hampshire (2015). They found that Cobra consistently produced relatively low percentages of unmarketable fruit over the three-year study. In addition, Arbason had among the highest marketability in at least two out of the three years of the study.

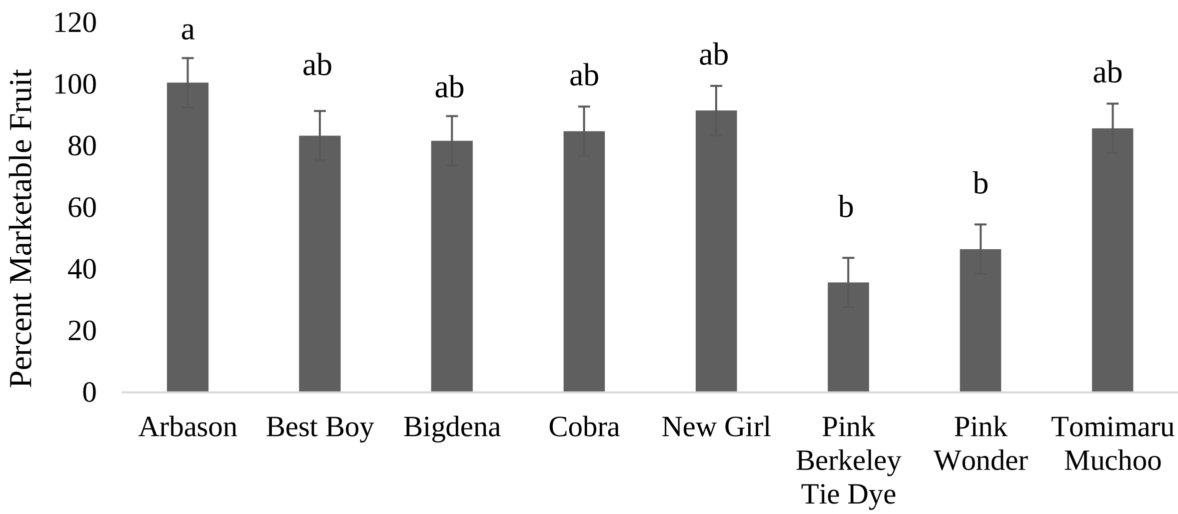

Figure 2.1. Marketability analysis of tomato cultivars grown under high tunnel conditions at Nesson Valley in 2016 and 2017. Means followed by the same letters are not significantly different at P<0.05 using Tukey's honestly significant difference test. SE bars indicate the mean ± 4.65 (n=4).

Field trial. The ideal 24-hour average temperature for a tomato plant is 19 °C. The developing flowers of a tomato plant are sensitive to temperatures above 30°C which may cause pollen sterilization and below 15°C which can lead to abnormalities and plant setback (Mefferd, 2017). Most tomato fruits develop 32-60 days after anthesis depending on cultivar (Welbaum, 2014). Although growing degree days (GDD) are sometimes used to schedule planting and harvesting of processing field tomatoes, optimal daytime and nighttime temperatures remain critical for fruit ripening. The critical temperature range of 20-24°C is necessary for fruit maturation and color development (Welbaum, 2014). Tomato fruits are climacteric and thus, ripening begins when triggered by the hormone ethylene (Brady, 1987).

High tunnels mediate fluctuating air temperatures by warming the air underneath the plastic faster than it can escape, thereby mitigating the drastic temperature changes from daytime to nighttime. In this regard, there should be less variability between the high tunnel trials compared to the field trials at each respective location. Without this buffering effect, the field trials experienced much greater variability which was evident by plant mortality and overall yield. In 2016, the cultivar, Pink Wonder experienced a higher plant mortality at NV and was subsequently removed from the statistical analysis for average yield.

The main effects of environment and cultivar were significant for average yield per plant (Appendix Table A.4). Cultivar by environment interactions occurred for both average number of fruit per plant and for average fruit weight per plant.

Despite being planted one week sooner in 2017, greater average yield per plant occurred at ABS in 2016 (Table 2.7). At NV, yields were greater in 2017 than in 2016 although not statistically different than ABS 17. The cultivar Cobra produced the greatest yield at 3.9 kg/plant but was not statistically different than Arbason, Best Boy, and Bigdena. The cultivars that produced the lowest yield were New Girl and Tomimaru Muchoo though not differing from Best Boy, Bigdena, and Pink Berkeley Tie Dye.

Table 2.7. Influence of the main effects of environment and cultivar on yield harvested per plant for field tomato trial conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar	Avg. yield/plant	Environment	Avg. yield/environment
Arbason	3.7 ab[z]	ABS 16[y]	6.4 a
Best Boy	3.2 abc	NV 16	0.9 c
Bigdena	3.1 abc	ABS 17	2.6 b
Cobra	3.9 a	NV 17	2.7 b
New Girl	2.7 c		
Pink Berkeley Tie Dye	2.8 bc		
Tomimaru Muchoo	2.5 c		

[z]Within a column, means followed by the same letters are not significantly different at P<0.05 using Tukey's honestly significant difference test (n=4).
[y]ABS 16= Absaraka 2016, NV 16= Nesson Valley 2016, ABS17=Absaraka 2017, NV17=Nesson Valley 2017.

When the cultivar by environment interaction for average number of fruit per plant is sliced, the resulting p-values indicate that all cultivars performed differently in at least one environment. When the interaction is sliced by environment, the p-values indicate a significant cultivar response to the environment ABS 16 (Table 2.8).

Table 2.8. P-values for slices of the cultivar by environment interaction of the main effect average number of tomato fruit harvested per plant in the field trials conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar-specific tests		Environment-specific tests	
Cultivar	P-value[z]	Location, Year	P-value[y]
Arbason	<.0001	Absaraka, 2016	<.0001
Best Boy	<.0001	Nesson Valley, 2016	0.923
Bigdena	<.0001	Absaraka, 2017	0.0873
Cobra	<.0001	Nesson Valley, 2017	0.6183
New Girl	<.0001		
Pink Berkeley Tie Dye	0.0005		
Tomimaru Muchoo	<.0001		

[z]Each cultivar specific test compares the average responses of a cultivar across four environments; each test has three numerator degrees of freedom.
[y]Each environment-specific test compares the average response of seven cultivars in the specified environment; each test has six numerator degrees of freedom.

On average, fruit production tended to be higher at ABS 16, followed by ABS 17, NV 17 and NV 16 (Table 2.9). The cultivars that produced the most fruit/plant at ABS in 2016 was Cobra and New Girl with 55 tomatoes per plant each, however, the number of fruit/plant from ‘Arbason’ was statistically similar to the number of fruit per plant from ‘Cobra’ and ‘New Girl’. At NV 16 and 17, the cultivars Bigdena and Tomimaru Muchoo, and Bidgena and New Girl, were found to be statistically different from one another, respectively. At ABS 17, ‘New Girl’ produced the most number of fruit per plant, but was not statistically different than ‘Arbason’.

When the cultivar by environment interaction for average fruit weight per plant is sliced, the resulting p-values indicate all the cultivars except Arbason and New Girl performed differently in at least one environment (Table 2.10). When the interaction is sliced by environment, the p-values indicate a significant cultivar response to all four environments.

Table 2.9. Average number of fruit harvested per cultivar in field trials conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar	ABS 16[z]		NV 16		ABS 17		NV 17	
	No./plant							
Arbason	54	a[y]	5	ab	18	ab	14	ab
Best Boy	36	b	5	ab	7	d	13	ab
Bigdena	32	b	10	a	11	dc	7	b
Cobra	55	a	8	ab	15	bc	11	ab
New Girl	55	a	7	ab	21	a	18	a
Pink Berkeley Tie Dye	28	b	4	ab	9	d	12	ab
Tomimaru Muchoo	41	b	3	b	15	bc	11	ab

[z] ABS 16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017, NV17=Nesson Valley 2017.
[y]Within a column means followed by the same letter are not significantly different at P<0.05 using Tukey's honestly significant difference test (n=4).

Table 2.10. P-values for slices of the cultivar by environment interaction of the main effect average fruit weight per plant in field trials conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar-specific tests		Environment-specific tests[y]	
Cultivar	P-value[z]	Location, Year	P-value
Arbason	0.1389	Absaraka, 2016	0.0074
Best Boy	<.0001	Nesson Valley, 2016	0.0007
Bigdena	<.0001	Absaraka, 2017	<.0001
Cobra	0.0022	Nesson Valley, 2017	<.0001
New Girl	0.8614		
Pink Berkeley Tie Dye	0.0321		
Tomimaru Muchoo	0.036		

[z] Each cultivar specific test compares the average responses of a cultivar across four environments; each test has three numerator degrees of freedom.
[y] Each environment-specific test compares the average response of seven cultivars in the specified environment; each test has six numerator degrees of freedom.

When the data is separated by experiment, the fruit weights were heavier on average in 2017 than in 2016 (Table 2.11). At ABS 16 the cultivar Best Boy on average produced the heaviest fruit, but was not significantly different than Bigdena. The cultivar New Girl produced the smallest fruits on average. At NV 16 and ABS 17, the cultivar Pink Berkeley Tie Dye produced the heaviest fruit, however, was not significantly different than cultivars Bigdena and Best Boy at ABS 17 nor Arbason, Bigdena, Cobra and Tomimaru Muchoo at NV16. The cultivar Bigdena produced the heaviest fruit weight of 339 grams at NV 17.

Table 2.11. Average fruit weight per plant in field trials conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar	ABS 16[z]		NV 16		ABS 17		NV 17	
	weight (g)							
Arbason	146	cd[y]	190	ab	166	c	211	cd
Best Boy	200	a	104	c	252	ab	280	b
Bigdena	182	ab	155	abc	259	a	339	a
Cobra	157	c	159	abc	226	b	253	bc
New Girl	101	e	108	bc	116	d	124	e
Pink Berkeley Tie Dye	178	b	238	a	258	a	220	cd
Tomimaru Muchoo	127	d	152	abc	158	c	207	d

[z] ABS16=Absaraka 2016, NV 16=Nesson Valley 2016, ABS 17=Absaraka 2017, NV 17=Nesson Valley 2017.
[y]Within a column means followed by the same letter are not significantly different at P<0.05 using Tukey's honestly significant difference test (n=4).

The marketability analysis showed that while only statistically different than three other cultivars, Arbason produced the most marketable fruit at 95% (Figure 2.2). The cultivar with the lowest marketability at 55% was Pink Berkeley Tie Dye, the only open pollinated cultivar described by the seed source as having "soft" fruit and no disease resistance, but was not statistically different than Tomimaru Muchoo.

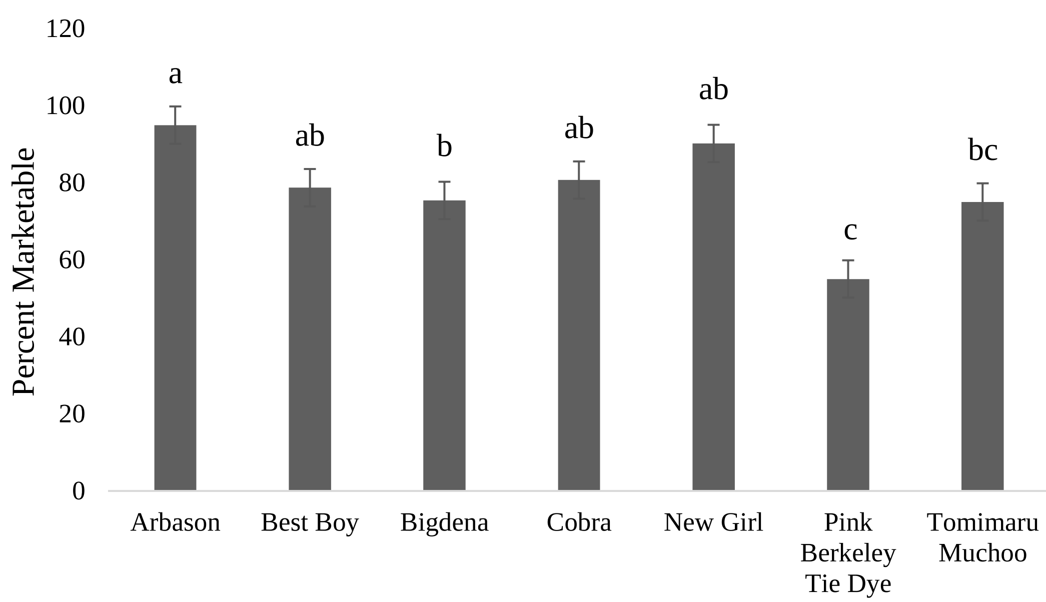

Figure 2.2. Marketability analysis of tomato cultivars grown under field conditions at Nesson Valley in 2016 and 2017. Analysis expressed in percent of total fruit harvested. Means followed by the same letters are not significantly different at P<0.05 using Tukey's honestly significant difference test. SE bars indicate the mean ± 2.86 (n=4).

Conclusions

This research provides information as to how the selected tomato cultivars would perform under high tunnel and field conditions in the NGP regions of North Dakota. Limited trial years and lack of consistency between locations merit further research in order to recommend a cultivar that will reliably produce high yields for the fresh market. Even though further research is suggested, the tomato yields observed with the high tunnel were 1.4 times greater compared to the tomato cultivar yields in the field. The high tunnels lengthened the season on average by 26 days and increased the harvest window by approximately five weeks. The results of this study demonstrates good tomato production potential for high tunnels in the NGP.

CHAPTER 3: PEPPER

Introduction

Peppers are warm-season, frost-sensitive perennials grown as annuals in short-season areas for their fruit which is classified botanically as a berry (Welbaum, 2015). The most prominent characteristic for the pepper fruit is its flavor, which ranges from sweet and mild to very pungent and spicy. The most widely cultivated and economically important species is *Capsicum annuum* L. which includes cultivars of all shapes, sizes, colors and taste.

Due to the wide range of fruit and plant types, it is difficult to classify peppers. They are often divided into pungent and non-pungent types (Welbaum, 2015). The most popular and well recognized of the non-pungent types is the large, blocky three to four-lobed bell peppers. In the US and Europe, this is the most economically important type, making up the largest portion of commercial fresh market volume.

High tunnels are semi-permanent structures covered in plastic that help moderate drastic temperature fluctuations by heating the air, plants and soil underneath the plastic; subsequently warming the air faster than it can escape and thereby increasing day and night temperatures (Blomgren and Frisch, 2007; Carey et al., 2009; Knewtson et al., 2010; Lamont, 2009). There is no published, peer-reviewed research on high tunnel production in North Dakota, and there is limited production information from regions with comparable climates. North Dakota's climate is heavily influenced by its location as the geographic center of North America within the NGP, and is characterized by extreme day to day fluctuations in temperature and a short growing season (Enz, 2003). The northeast and north-central parts of the state have about 110 days in the growing season, while the rest of the state has around 120 days.

The movement for locally grown produce nationwide can be seen by the number of farmers markets appearing in each state. The United States Department of Agriculture National Farmers Market Directory (2018) has over 8,600 registered farmers markets across the nation. Though North Dakota has been largely recognized for its agricultural commodities, it is no stranger to the push for local foods. There are over 50 farmers markets across the state with more than 125 producers contributing to local markets (J. Good, personal correspondence, December 20, 2018). This, along with a current population increase of up to 12.3% since the 2010 United States Census, will continue to be the driving force for more local vegetable growers. The high economic value, consumer local food movement, as well as the consistency and predictability of crop quality will continue to drive production of bell peppers grown in high tunnels.

The objectives of this trial were to evaluate nine commercially available bell pepper cultivars in two locations representing eastern and western North Dakota to be conducted as side-by-side trials of outdoor field and indoor high tunnel production.

Methods and Materials

Site Description. The experiment was conducted in the 2016 and 2017 growing seasons at two separate locations in North Dakota representing the east and west climatic regions of the state. Within the NGP, the state of North Dakota falls within three distinct ecological sub-regions or ecoregions which are defined by Omernick (1987) as the Northwestern Great Plains, Northwestern Glaciated Plains and Northern Glaciated Plains. Of those three ecoregions, the trial locations are representative of the climatic conditions of the Northwestern Glaciated Plains (western) and the Northern Glaciated Plains (eastern) regions.

The western location was at the NDSU Williston Research Extension Center (WREC) Nesson Valley Irrigation Research and Development Project (48°09’44.1” N and 103°06’29.7”

W) near Williston, ND in Williams County (“NV”). This region is characterized by a semiarid climate with low humidity, frequent drying winds, low rainfall, abundant sunshine, hot summers and cold winters (Tollerud et al., 2018). Annual average precipitation is approximately 250 mm.

The eastern location was at the NDSU Dale E. Herman Research and Arboretum farm (46°59’28” N and 97°21’20” W) near Absaraka, ND (“ABS”) in Cass County. This region is characterized as continental, that is hot or warm summers and cold winters with an average annual precipitation range between 380 and 760 mm (Tollerud et al., 2018). The total rainfall, daily maximum, and minimum air temperatures from May to September were recorded by North Dakota Agricultural Weather Network (NDAWN) for the two locations and years can be found in Appendix Figures A.3 and A.4.

Additional information on each location, high tunnel size and soil classification can be found in Appendix Table A.1. One high tunnel was constructed at each site in the fall of 2015 and completed in the spring of 2016. Both high tunnels (Northpoint, Rimol Greenhouse Systems, Inc. Hooksett, NH) were built in a north-south orientation with 13 gauge steel framework; double air inflated 4 year-rated 6 mil clear polyethylene greenhouse film treated with anti-condensate and ultraviolet features; and nominal lumber-framed end walls, baseboards and hip boards. Ventilation was accomplished by thermostatically controlled electric roll up sidewalls running the lengths of both sides set to open at 27°C, and motorized shutter vents in each gable end wall set to open at 21°C. Sidewalls were manually closed during high wind and storm events when deemed necessary.

Site Preparation. Prior to planting, each location collected soil cores to a depth of 30 cm and submitted them to the NDSU Soils Testing Lab (Fargo, ND) for a basic soil nutrient test (Appendix Table 1.2). The 2014 Midwest Vegetable Production Guide (Engel et al., 2014) was used for determining nutrient recommendations of N-P-K. A split application of N applied pre-plant, broadcasting granular 46% Urea fertilizer and incorporating it into soil, and the rest of the N was applied during the growing season as fruit development began. The post-planting fertilizer application used liquid 28% UAN injected into the irrigation system and applied to drip-irrigated peppers. Prior to planting, beds were tilled and formed using rotor-tiller equipment. All plantings were in single rows with one line of 15 mil drip tape (Toro® Aqua-Traxx, DripWorks, Willits, CA) with emitters spaced 20.3 cm on center with a 2.15 x 10^{-4} m^3/s flow rate that were installed after transplanting. The irrigation from planting until the end of June was scheduled on Monday, Wednesday and Friday. At the beginning of July, irrigation as reduced to twice a week for 5 hours. Weed management was accomplished using a 15-year, 3 oz. woven weed barrier (Agriculture Solutions, Strong, ME) laid on either side of the row and hand labor as needed.

Temperature. Weather data and soil temperatures were monitored in the field using the North Dakota Agricultural Weather Network (NDAWN). The NV location used the Hofflund Station located at 590 m elevation. The ABS location used the Prosper Station with an elevation of 284 m above sea level. The NDAWN station temperature and relative humidity sensors were set at 1.5 m from the soil surface. Soil temperature readings were taken at a depth of 10 cm for bare soil. A WatchDog 1000 series micro station (Spectrum Technologies, Inc. Aurora, IL) was used at the NV high tunnel to monitor air temperature, relative humidity and soil temperatures. A Decagon EM50 data logger (Decagon Devices, Inc., Pullman, WA) was set up at ABS to monitor inside and outside air temperature readings. Both data loggers were set up to be comparable to the NDAWN stations for air temperature.

Plant Materials. The high tunnels used for this trial also housed independent tomato, cucumber, and cut flower cultivar trials occurring simultaneously for a total area of 232 m^2 under protection. For the indoor high tunnel (HT) and the outdoor field (FD) trials, nine bell pepper cultivars were selected (Johnny's Selected Seeds Winslow, ME). Cultivar names, disease resistance codes, production type, average fruit weight and days to maturity are presented in Table 3.1.Due to the discontinuation of the cultivar Moonset in 2017, the cultivar Early Sunsation was substituted in its place. These cultivars were removed from the statistical analysis in order to combine years. The cultivars Sprinter and Moonset were categorized as "heated tunnel production" bell peppers (Johnny's Selected Seed, 2016). These types are genetically more vigorous and able to perform under a variety of weather conditions. The rest of the cultivars selected were widely adapted for field or high tunnel production. The cultivar California Wonder was open pollinated; the rest were F1 hybrids.

Table 3.1. Pepper trial cultivar, seed source, days to maturity, color and fruit size according to Johnny's Selected Seed (2016).

Cultivar	Seed source[y]	Disease resistance[x]	Days to initial/ripe[w]	Color	Fruit size
Ace F_1 [z]	JSS[y]	--	50/70	Green/Red	Medium
California Wonder	BS	--	75	Green/Red	Large
Flavorburst F_1	JSS	--	67/87	Green/Yellow	Med-large
Intruder F_1	JSS	BLS 1-3, TEV, TMV, PC.	62/72	Green/Red	Large
Islander F_1	JSS	TMV	56/81	Purple/Red	Medium
King Arthur F_1	JSS	BLS 1, 2, PVY	59/79	Green/Red	Large
Moonset F_1	JSS	TM 0-2	60/80	Green/Yellow	Large
Sprinter F_1	JSS	TM 0-3	60/80	Green/Red	Large
X3R® Red Knight F_1	JSS	BLS 1-3, PVY, TMV	57/77	Green/Red	Large
Early Sunsation F_1	RS	BLS	69	Green/Yellow	Large

[z] Refers to F_1 hybrid.
[y]JSS= Johnny's Selected Seed. BS=Burpee Seed. RS=Reimer Seeds.
[x] BLS=Bacterial Leaf Spot races 1-3, PC=Phytopthora Root Rot, PVY=Potato Virus Y, TM=Tobamovirus races 0-3, TMV=Tobacco Mosaic Virus.
[w] Initial green/ ripe.

Transplant Establishment. In 2016, pepper seeds were started in the North Dakota Agricultural Experiment Station (NDAES) greenhouses in Fargo, ND (20 ± 2°C, 16:8 L:D, RH = 40-65%) in 606-deep cell packs (T.O. Plastics, Clearwater, MN) filled with a growing medium (PRO-MIX FLX, Premier Horticulture Inc., Quakertown, PA) and transplanted at 4 weeks into

SVD-450 molded plastic pots (T.O. Plastics, Clearwater, MN) filled with the same growing medium. Plants were not fertilized but watered with tap water once a week (100 mL). Half of the seedlings were transported to NV location and the other half were taken to the ABS location after 8 weeks of development. The timing of the high tunnel construction extended beyond the anticipated planting date, resulting in more mature seedlings at the time of transplanting on 25 May at both locations for the high tunnel and field trials.

In 2017, seedlings for the ABS location were started in the NDAES greenhouse while seedlings for the NV location were started at WREC under indoor fluorescent lighting (40W Gro-Lux Wide Spectrum, Sylvania Ontario, Canada). In an effort to reduce seed borne viruses, the seeds at both locations were treated with a 10% solution of trisodium phosphate (TSP, Savogran Company, Norwood, MA) for 15 min. and rinsed in cold water. The seeds were then air-dried overnight and seeded the next day into the same growing medium previously identified. At four weeks, the seedlings were transplanted at both locations on 3 and 11 May at ABS and NV, respectively in the high tunnels and on 15 and 26 May at ABS and NV, respectively for the field. At both locations and years, were transplanted were spaced at 61 cm centers within the row and a 91 cm spacing between rows At ABS, the extra 1.2 m high tunnel width allowed for two plants per plot, which were staked in a basket weave-like fashion using wooden stakes and nylon rope when the plants were approximately 40 cm tall.

Data Collection. Harvest took place weekly and was based on mature color per cultivar characteristics or if a fruit was marketable size and its growth would be obstructed by adjacent branches. Fruit quality and grade were measured using USDA vegetable grading standards for sweet pepper (USDA, 2005). The grades consisted of U.S. Fancy, U.S. No. 1 and U.S. No. 2 and were classified according to fruit size. To size the fruit, a measurement of the fruit diameter and fruit length were recorded and graded as follows: U.S. Fancy grade consisted of a diameter no less than 7.62 cm and a length no less than 8.89 cm, U.S. No. 1 grade with a diameter no less than 6.35 cm and length no less than 6.35cm, and U.S. No. 2 grade consisted of a diameter and length less than 6.35 cm.

Average yield in kilograms per plant were based on harvest weights collected. Average number of fruit were based on the total fruit harvested from each plant throughout the growing season. In the case of ABS yields from two plants per plot were averaged. The percent of marketable fruit were calculated as the difference between marketable and unmarketable fruit divided by the total and converted to a percentage Yields and total fruits from inside the high tunnel were compared to those grown in the field but were not statistically analyzed together. Each trial was treated as an independent study.

Experimental Design and Statistical Analysis

The trials were planted in a randomized complete block design with four replications for a total trial area of 17 m^2 (180 ft^2). The weight and number of fruit data collected for the cultivars Moonset in 2016 and Early Sunsation in 2017 were removed from the statistical analysis in order to combine years. The statistical analysis of data was performed using a linear model for SAS 9.4 (PROC GLIMMIX with the REML estimation method, SAS Institute, SAS Circle, Cary, NC) where cultivar and environments were considered fixed, and replications within environment were considered random effects. An environment was considered one experiment conducted at a specific location and a specific year. Mean separation was done through the PDIFF function standard error for a least significant difference calculation using Tukey's honestly significant difference pairwise comparison test. An alpha level of $p < 0.05$ was used for all hypothesis tests. The marketability analysis was determined using the Pearson chi-square test of independence.

The statistical analysis of data were performed using a two-way frequency table for SAS 9.4 (PROC FREQ, SAS Institute, SAS Circle, Cary, NC) and a correspondence analysis in order to visualize the non-independence in a table (PROC CORRESP SAS Institute, SAS Circle, Cary, NC).

Results and Discussion

High tunnel trial. The main effect of environment was significant for average yield per plant (Appendix Table A.5). Cultivar by environment interactions occurred for average number of fruit and for average fruit weight.

Plant yields in 2016 were greater than 2017 regardless of the location (Figure 3.1). The lower yield in 2017 was attributed to pest management difficulties. At NV in 2017, a severe infestation of green peach aphid (*Myzus persicae* Sulzer) occurred prompting the use of insecticides and horticultural oils. The plants were also in the same vicinity of virus infected tomato plants. Although some plants exhibited symptoms, no virus testing took place to confirm a diagnosis. At ABS in 2017, a severe outbreak of two-spotted spider mites (*Tetranychus urticae* Koch) occurred, prompting the use of diatomaceous earth and biological predatory mites, but the threshold of infestation had been surpassed by the time counteractive measures were enacted resulting in yield losses.

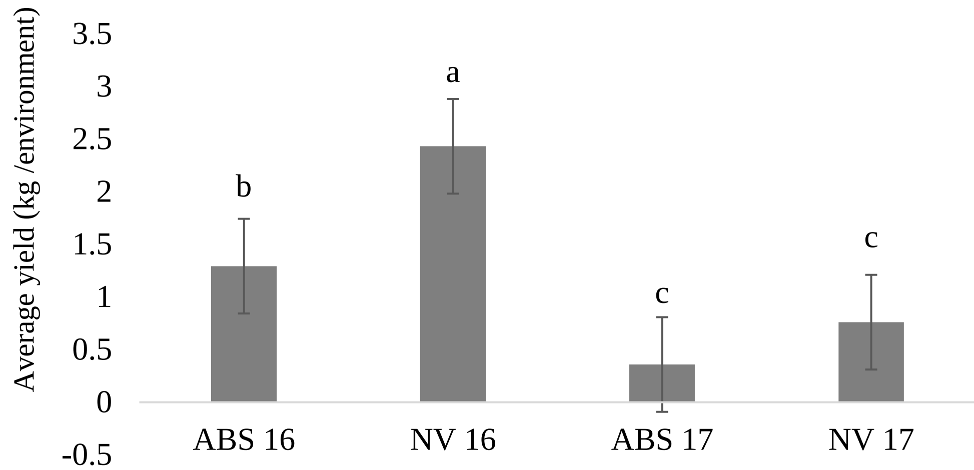

Figure 3.1. Average yield of bell peppers grown under high tunnel production at Absaraka and Nesson Valley, ND in 2016 and 2017. Means followed by the same letters are not significantly different at P<0.05 using Tukey's honestly significant difference test. SE bars indicate the mean ± 0.10 (n=4).

When the cultivar by environment interaction for average number of fruit harvested per plant is sliced, the resulting p-values indicate the cultivars Ace, Intruder, Islander and King Arthur performed differently in at least one environment (Table 3.2). When the interaction is sliced by environment, the p-values indicate a significant cultivar response to the environment NV 16.

There was no difference found in the average number of bell peppers harvested per cultivar at ABS in 2016 (Table 3.3). The cultivar Islander produced three times more fruit in 2016 at NV compared to the same location in 2017. The cultivar Ace produced statistically more fruit than Flavorburst, Intruder, Islander, King Arthur and X3R Red Knight in ABS 2017. The cultivar Ace was also a top producer at NV 17 but was not significantly more than Flavorburst, and Islander. The cultivar Islander is described by the seed company as a medium-sized fruit having lavender-colored skin and ripens in 56 days, but is physiologically mature when red at 81 days (Johnny's Selected Seed, 2016). Due to its appealing lavender color and smaller size, ‘Islander’ was harvested at purple-ripe versus mature-red which impacted the total number of fruit. Frequent harvesting makes room for new flowers and fruit set to occur more rapidly (Welbaum, 2015).

Table 3.2. P-values for slices of the cultivar by environment interaction for main effect average number of fruit harvested per plant for field bell pepper trial conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar-specific tests		Environment-specific tests	
Cultivar	P-value[y]	Location, Year	P-value[z]
Ace	<.0001	Absaraka, 2016	0.8682
California Wonder	0.3052	Nesson Valley, 2016	<.0001
Flavorburst	0.1575	Absaraka, 2017	0.9696
Intruder	0.02	Nesson Valley, 2017	0.1146
Islander	<.0001		
King Arthur	0.0011		
Sprinter	0.1818		
X3R Red Knight	0.2492		

[z]Each cultivar specific test compares the average responses of a cultivar across four environments; each test has three numerator degrees of freedom.
[y]Each environment-specific test compares the average response of seven cultivars in the specified environment; each test has six numerator degrees of freedom.

Table 3.3. Average number of bell pepper fruit harvested per cultivar grown under high tunnel production in Absaraka and Nesson Valley, ND in 2016 and 2017.

Cultivar	ABS 16[z]		NV 16		ABS 17		NV 17	
	------------------------ No./plant -------------------------							
Ace	12	a[y]	27	b	6	a	13	a
California Wonder	7	a	11	c	5	ab	6	b
Flavorburst	10	a	11	c	4	bc	9	ab
Intruder	11	a	14	c	4	bc	5	b
Islander	9	a	39	a	4	bc	13	a
King Arthur	9	a	16	c	3	c	5	b
Sprinter	12	a	10	c	5	ab	5	b
X3R Red Knight	9	a	9	c	3	c	6	b

[z] ABS16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017, NV17=Nesson Valley 2017.
[y]Within a column means followed by the same letter are not significantly different at P<0.05 using Tukey’s honestly significant difference test (n=4).

When the cultivar by environment interaction for average fruit weight per plant is sliced, the resulting p-values indicate all the cultivars except Islander performed differently in at least one environment (Table 3.4). When the interaction is sliced by environment, the p-values indicate a significant cultivar response to all environments except ABS 17.

Table 3.4. P-values for slices of the cultivar by environment interaction for average fruit weight of bell peppers harvested per cultivar under high tunnel production at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar-specific tests		Environment-specific tests	
Cultivar	P-value[z]	Location, Year	P-value[y]
Ace	0.0118	Absaraka, 2016	0.0004
California Wonder	<.0001	Nesson Valley, 2016	<.0001
Flavorburst	0.0046	Absaraka, 2017	0.2089
Intruder	<.0001	Nesson Valley, 2017	0.0032
Islander	0.4666		
King Arthur	<.0001		
Sprinter	<.0001		
X3R Red Knight	<.0001		

[z]Each cultivar specific test compares the average responses of a cultivar across four environments; each test has three numerator degrees of freedom.
[y]Each environment-specific test compares the average response of seven cultivars in the specified environment; each test has six numerator degrees of freedom.

Fruit weight was on average higher in 2016 than in 2017 (Table 3.5). In 2016 at NV, ‘Sprinter’, and ‘X3R Red Knight’ produced heavier fruit, averaging more than 200 grams but were significantly different than ‘California Wonder’. Larger fruit was produced in 2016 for both locations compared to 2017. Although not statistically greater in every environment, the cultivar X3R Red Knight produced the largest fruit in three out of the four environments.

Table 3.5. Average fruit weight of bell peppers harvested per cultivar under high tunnel production at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

	ABS 16[z]		NV 16		ABS 17		NV 17	
Cultivar	---------------------- Avg. Fruit wt.(g)/plant ------------------------							
Ace	96	c[y]	124	de	110	a	69	d
California Wonder	147	ab	203	ab	93	a	93	c
Flavorburst	125	b	148	cd	91	ab	98	c
Intruder	139	ab	171	bc	88	ab	91	cd
Islander	87	c	111	e	109	a	106	bc
King Arthur	143	ab	166	bc	69	b	122	b
Sprinter	143	ab	208	a	105	a	107	bc
X3R Red Knight	149	a	228	a	103	a	142	a

[z] ABS16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017, NV17=Nesson Valley 2017.
[y]Within a column means followed by the same letter are not significantly different at P<0.05 using Tukey’s honestly significant difference test (n=4).

There are several unpublished cultivar trial research reports on high tunnel bell pepper production from New York, New Hampshire, Iowa, Kansas and Utah with different selections of cultivars and/or management practices. The primary objective of each of these trials was to evaluate cultivar performance in terms of production and marketability in each respective state. For example, the University of New Hampshire Cooperative Extension publication (2016) cited 'Sprinter' as producing an average of 1.7 kg per plant and an average fruit size of 246.64 grams which corresponded to our research study in which 'Sprinter' produced an average of 1.2 kg/plant and an average fruit size of 208 grams at NV in 2016 (the overall average across years and locations was 141 grams). The researchers in New Hampshire, however, harvested each fruit once it was at least 20% colored, giving the fruit more time to grow.

In another variety trial conducted in a Kansas high tunnel, 'Intruder' and 'Red Knight' were found to have fruit sizes of 122.5 and 113 g per fruit; yielding 4.8 and 5.6 kg/plant; and producing 39 and 50 fruit/plant, respectively. These numbers differ from our study; however, Kansas has a very warm and longer growing season which should have benefitted the pepper yields. Peppers in stressful conditions, specifically low temperatures (below 10°C) will stop growing (Welbaum, 2015; Mefferd, 2017). Peppers do, however, tolerate a higher growing temperature than tomatoes and will continue to grow at 20-25°C (Welbaum, 2015).

The marketability analysis yielded a significant chi-square statistic (<0.0001, data not shown) indicating differences between the observed and expected fruit grades for the various cultivars. According to the correspondence analysis shown in Figure 3.2, the cultivars Ace and Islander were expected to produce the most U.S. No. 2 grade peppers; X3R Red Knight was expected to produce the most U.S. Fancy, while Flavorburst was expected to produce the most U.S. No. 1 grade peppers.

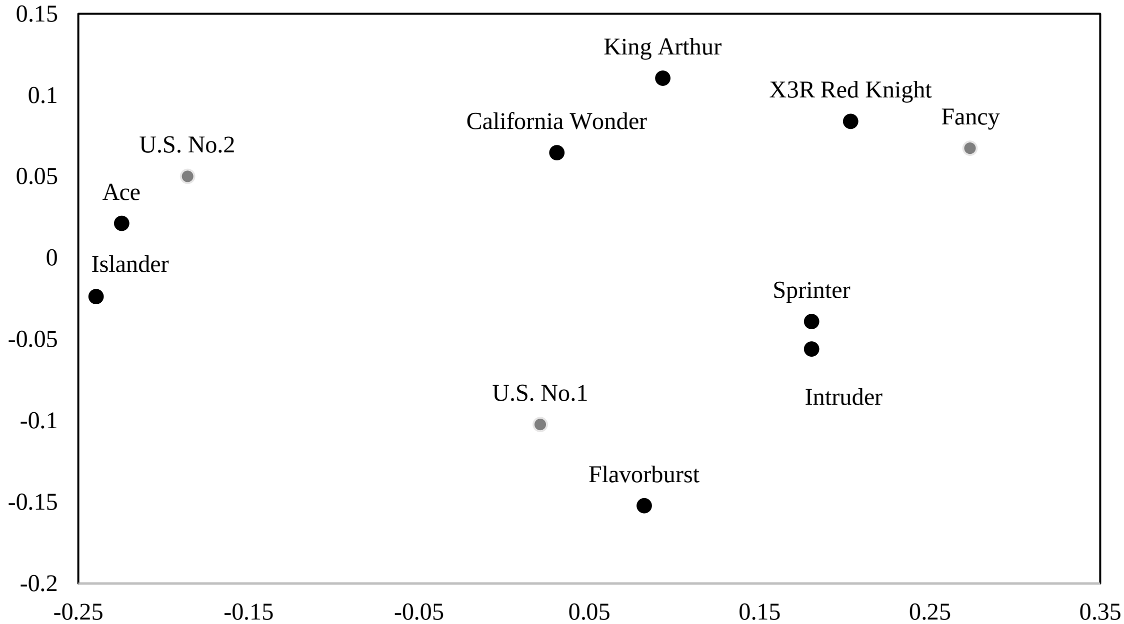

Figure 3.2. Correspondence analysis of the two-way frequency table for bell peppers trial grown under high tunnels conditions in Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

The observed fruit grades showed ‘Ace’ and ‘Islander’ as producing the most U.S. No. 2 grades, however, there was no cultivar that produced more U.S. Fancy peppers than any other grade although X3R Red Knight was expected to (Figure 3.3). The cultivars Flavorburst, Intruder and Sprinter did produce the most U.S. No. 1 grade peppers. The results did not produce any significant statistical differences among the cultivars.

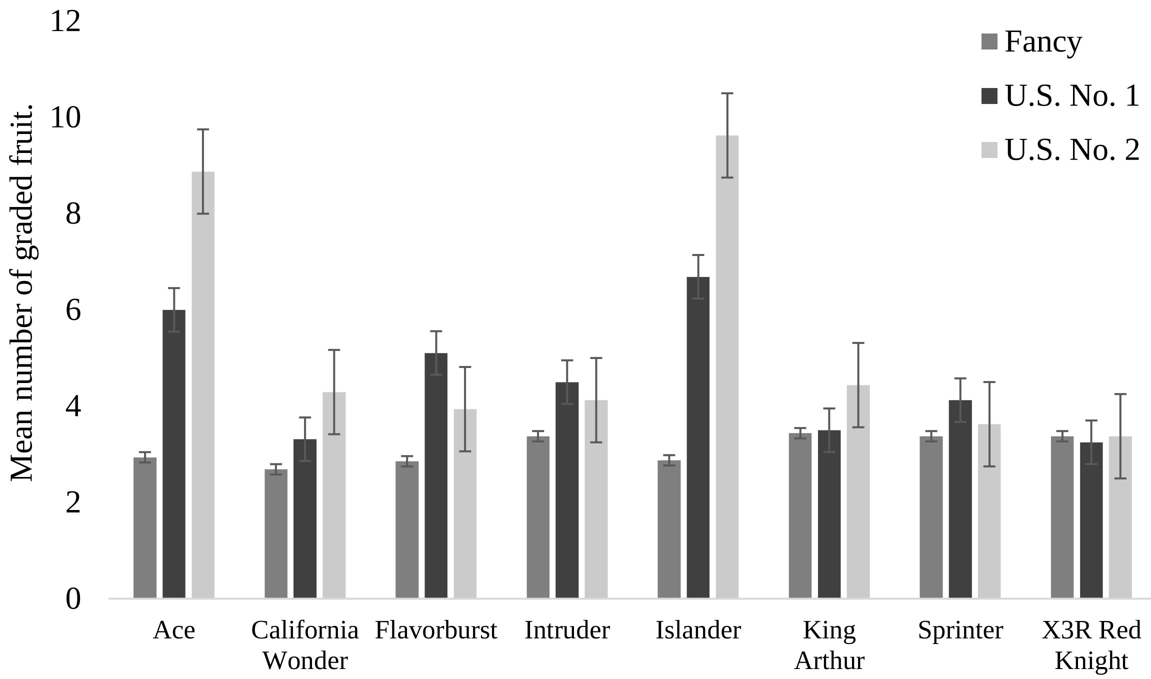

Figure 3.3. Mean number of fruit harvested from high tunnel trials conducted at Absaraka and Nesson Valley, ND in 2016 and 2017, and categorized according to the USDA grading standards. SE bars indicate the mean ± 0.32 (n=4).

Field trial. The ideal mean daily temperature for a pepper plant is 20-25°C (Walbaum, 2015). Growing a pepper plant below 16 °C will cause the plant to shut down (Mefferd, 2017). The mean daily normal temperature calculated as average temperature minus normal average temperature by the National Weather Service and NDAWN for NV and ABS was 16°C for the growing season as 1 May to 30 September for both seasons (Appendix Figures A.1 and A.2). Because the construction of the high tunnels delayed the plantings, both locations were planted on 25 May 2016 and experienced a +1.9°C and -2.3°C respective departure from normal. In 2017, an earlier planting date of 15 May at ABS showed a +6.1°C departure from normal and on 20 May, just five days after transplanting, the average daily temperature was 7.57°C; a -6.8°C departure from normal. This fluctuation in temperature was considered an abiotic plant stress. Abiotic stressors such as drought, flooding, nutrient deficiencies, salinity, excessive radiation, winds and extreme temperatures are the principal factors that cause reduced plant growth and may decrease the average crop yield by 65-87% (Koyro et al., 2012; Leon-Chan et al., 2017; Shinozaki et al., 2015).

Thus in the field, the main effect of environment influenced average yield, fruit number and average fruit weight (Appendix Table A.6). Cultivar also influenced differences in both average fruit number and average fruit weight responses.

In ABS 2016, average yields and number of fruit per plant were six times greater on average than plant yield in ABS 2017 (Fig. 3.4 and 3.5). However, in NV 2017, yields and total fruit per plant were approximately double from plants in NV 2016. The cultivar Ace produced the most fruit per plant (Figure 3.6). The cultivar Islander produced the second most fruit per plant but was not statistically different from California Wonder and Flavorburst.

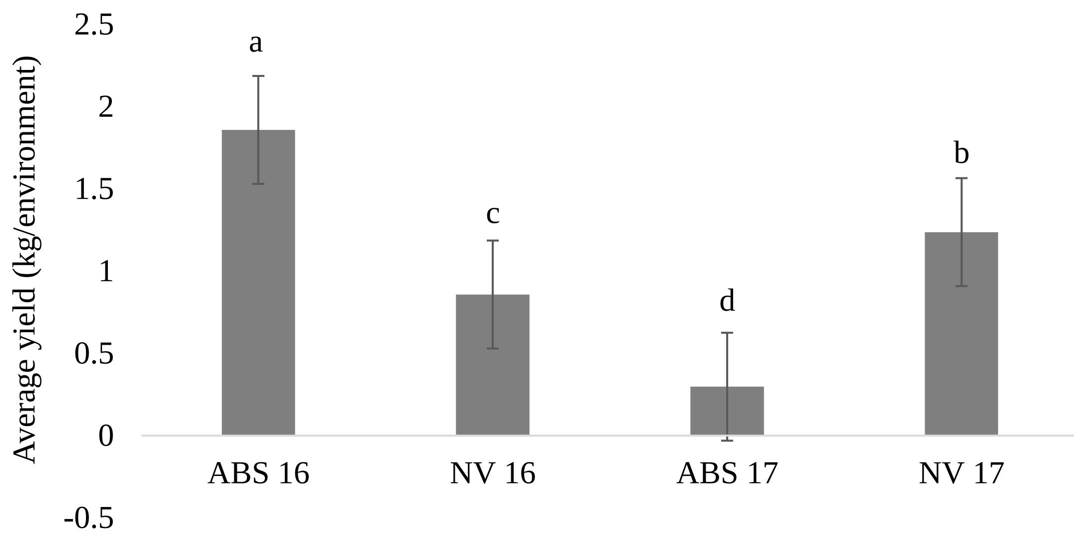

Figure 3.4. Average yield harvested from eight pepper cultivars per environment in field trials conducted at Absaraka and Nesson Valley, ND in 2016 and 2017. Means followed by the same letters are not significantly different at P<0.05 using Tukey's honestly significant difference test. SE bars indicate the mean ± 0.10 (n=4). ABS 16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017, NV17=Nesson Valley 2017.

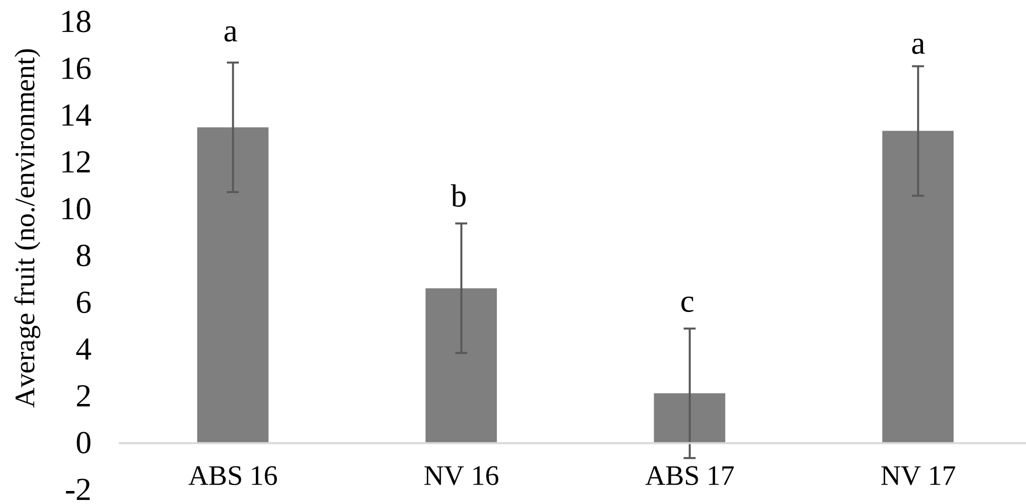

Figure 3.5. Average number of fruit harvested from eight pepper cultivars in field trials conducted at Absaraka and Nesson Valley, ND in 2016 and 2017. Means followed by the same letters are not significantly different at P<0.05 using Tukey’s honestly significant difference test. SE bars indicate the mean ± 0.60 (n=4). ABS 16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017, NV17=Nesson Valley 2017.

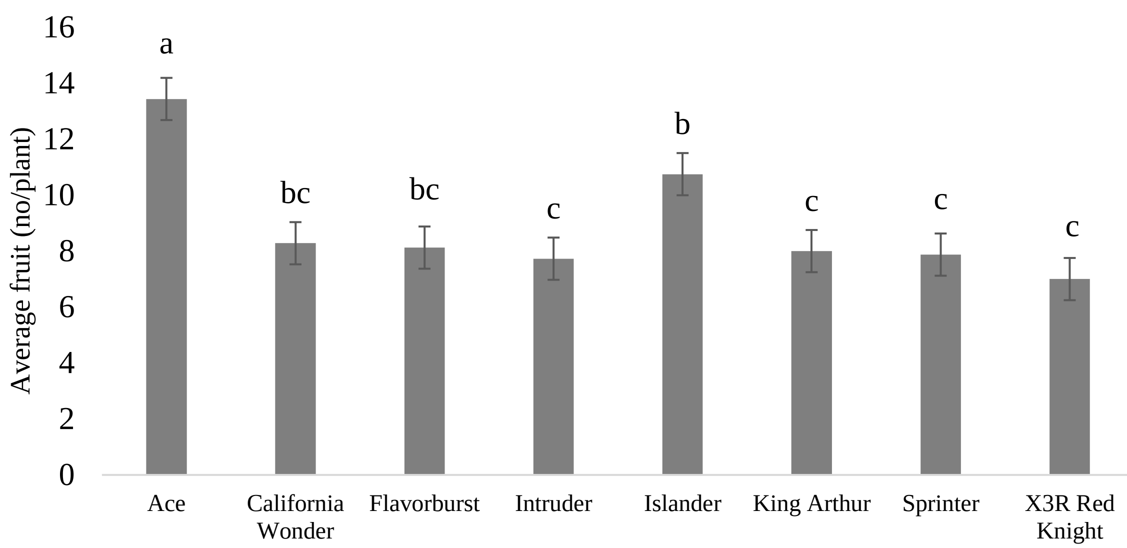

Figure 3.6. Average number of fruit harvested per cultivar in field trials conducted at Absaraka and Nesson Valley, ND in 2016 and 2017. Means followed by the same letters are not significantly different at P<0.05 using Tukey’s honestly significant difference test. SE bars indicate the mean ± 0.24 (n=4).

Fruit weight for NV 2017 were less on average than fruit weight for the other three environments (Figure 3.7). There was no significant difference in fruit size between ABS 16, ABS 17 and NV 16. The cultivar that produced the smallest fruit was Ace but was not significantly different from Islander (Figure3.8). The cultivar, Ace was among the cultivars with the most fruit produced in each environment and was expected to have the earliest days to maturity at 50 days until green ripe and 70 days until red mature medium sized fruit. According to the seed supplier, ‘Ace’ is considered “widely adapted, but performs particularly well in cool climates where bell peppers are difficult to grow successfully.”

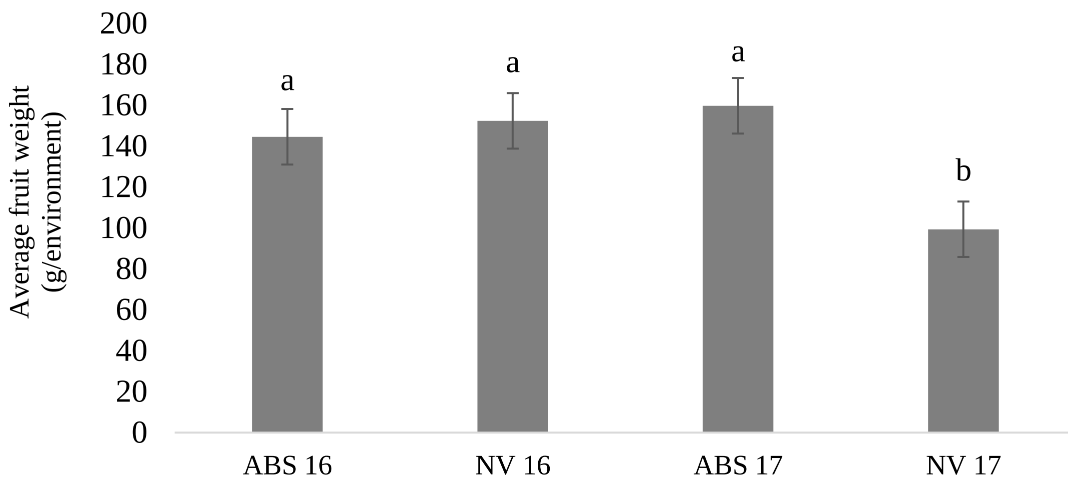

Figure 3.7. Average fruit weight in grams from eight pepper cultivars per environment in field trials conducted at Absaraka and Nesson Valley, ND in 2016 and 2017. Means followed by the same letters are not significantly different at $P<0.05$ using Tukey’s honestly significant difference test. SE bars indicate the mean ± 4.6 (n=4). ABS 16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017, NV17=Nesson Valley 2017.

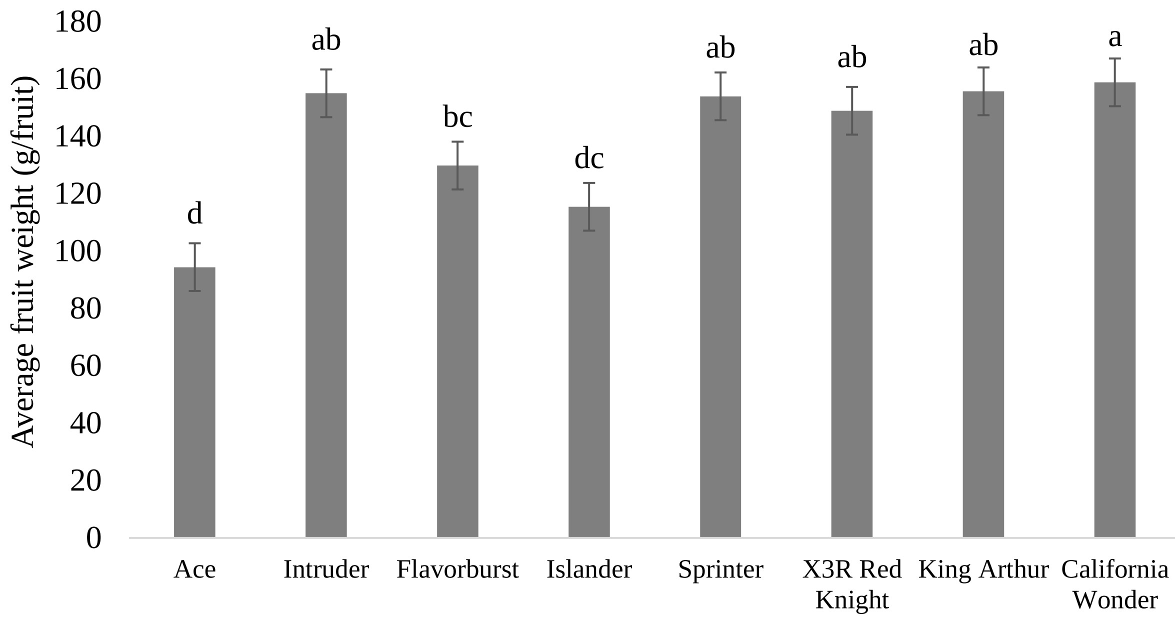

Figure 3.8. Average fruit weight per cultivar harvested from field trials conducted at Absaraka and Nesson Valley, ND in 2016 and 2017. Means followed by the same letters are not significantly different at P<0.05 using Tukey's honestly significant difference test. SE bars indicate the mean ± 0.24 (n=4).

The marketability analysis yielded a significant chi-square statistic (<0.0001, data not shown) indicating differences between the observed and expected fruit grades for the various cultivars. According to the correspondence analysis shown in Figure 3.9, the cultivars Ace and was expected to produce the most U.S. No. 2 grade peppers; Flavorburst and Intruder were expected to produce the most US No. 1 while X3R Red Knight was expected to produce the most U.S. Fancy.

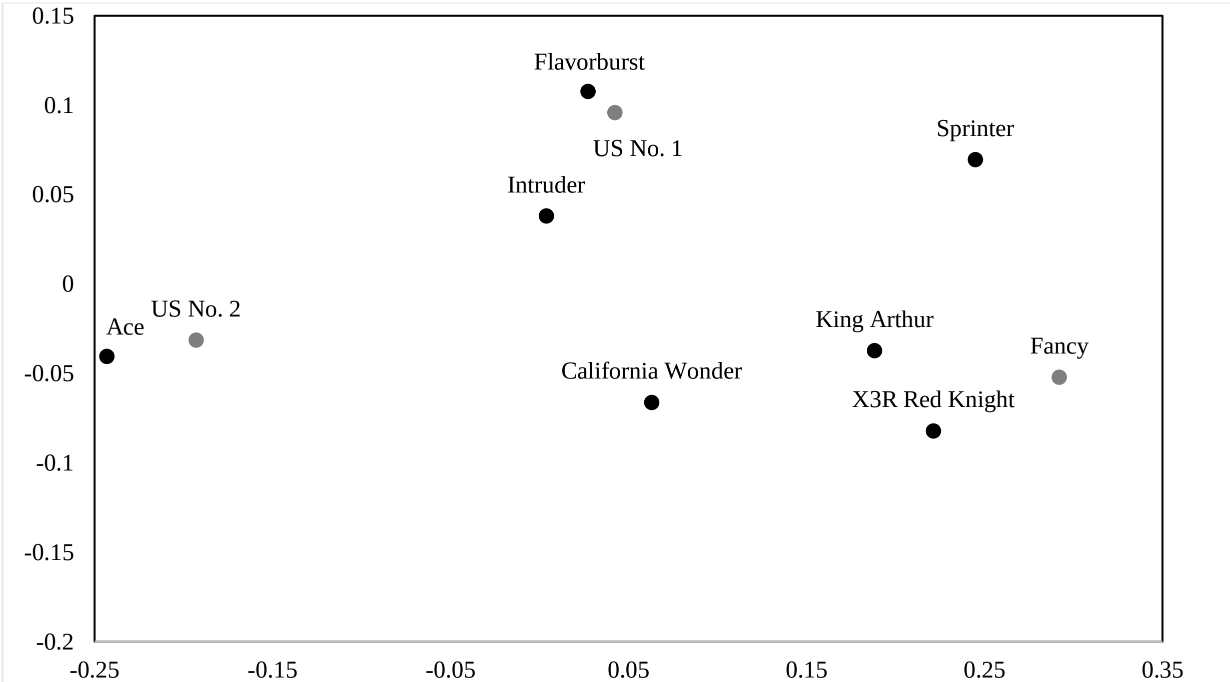

Figure 3.9. Correspondence analysis of the two-way frequency table for bell pepper trial grown under field conditions in Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

The observed fruit grades showed ‘Ace’ and ‘Islander’ as producing the most U.S. No. 2 grades, however, there was no cultivar that produced more U.S. Fancy peppers than any other grade although California Wonder, King Arthur and X3R Red Knight did produce more compared to U.S. No. 1 (Figure 3.10). All of the cultivars except Sprinter produced more U.S. No. 2 peppers than any other grade. The results did not produce any significant statistical differences among the cultivars.

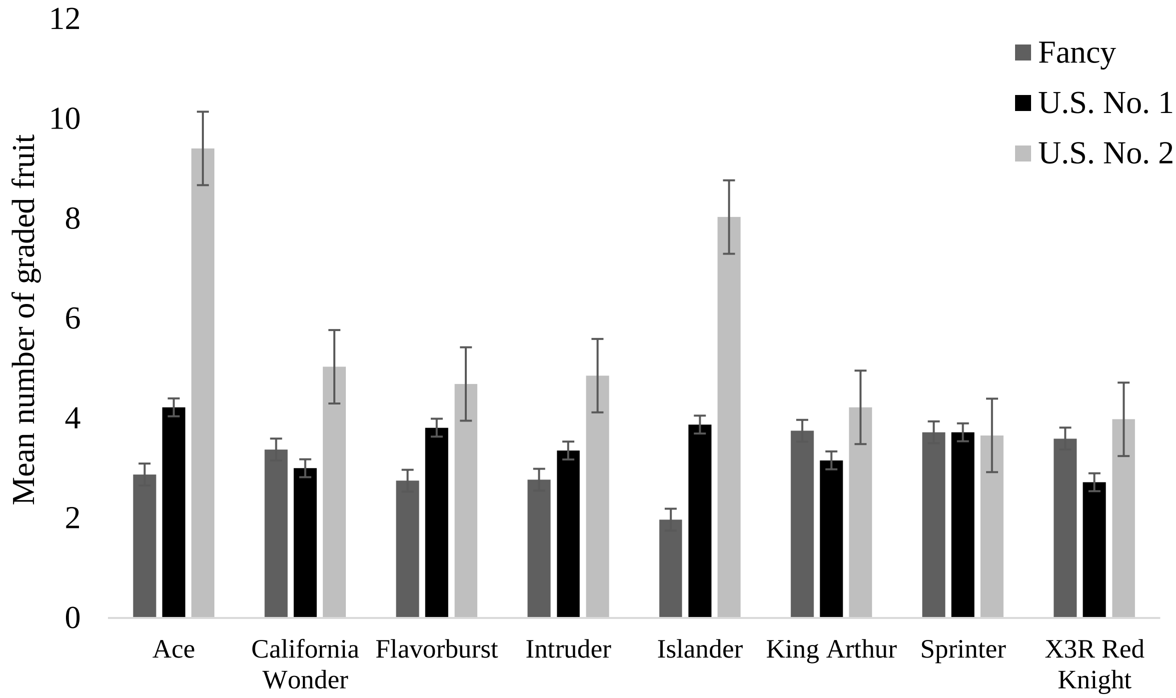

Figure 3.10. Mean number of fruit harvested from field trials conducted at Absaraka and Nesson Valley, ND in 2016 and 2017, and categorized according to the USDA grading standards. SE bars indicate the mean ± 0.57 (n=4).

Conclusions

The peppers appeared to have less variability in overall yield per plant in both the high tunnel and field trials which was attributed to plant uniformity of the fruit. In the high tunnel, the mean yield produced was 1.24 kg per plant with an average of 10 fruits harvested per plant. The mean fruit weight produced from the field was 1.06 kg per plant with an average number of fruit harvested of nine peppers per plant. These results support the findings of Taber et al. (2009) in their Iowa State University high tunnel colored pepper production trial. Researchers concluded that although high tunnels advanced pepper fruit maturity by approximately six weeks, it did not necessarily increase yields over the field trial. In a 2008-2009 Pennsylvania field pepper cultivar trial, sixteen cultivars were trialed in the central, southeastern and southwestern areas of the state. The cultivar Intruder performed similar to Intruder in the current trial with 9.78 peppers harvested per plant compared with 7.7 peppers in the current study, and 1.9 kg per plant as compared to 1.0 kg per plant (Sanchez, 2011).

The minor difference in pepper yields and totals between the high tunnel and field may be attributed to abiotic and biotic stress factors that were present during the trials. For example, at NV in 2016, the peppers inside the high tunnel became heavily infested with green peach aphids quickly surpassing the economic thresholds resulting in the need for weekly pesticide applications. In 2017, nearly all of the peppers were affected by virus infections reducing yields. In 2017 the high tunnel at ABS experienced a two-spotted spider mite outbreak to which control measures seemed ineffective.

Peppers are ranked as the third most popular vegetable chosen for high tunnel production (behind tomato and cucumber). Peppers, however, are a slower-growing, more generative plant-type that direct most of their energy toward fruit production rather than vegetation (Johnny's publication, 2016). In this respect, peppers have less vigor to help them overcome stressful growing conditions and plant energy can be consumed quickly by stressors such as cool night temperatures, overly hot day temperatures, irregular watering, etc. Under these situations, pepper plants can completely shut down, decreasing yields and putting them at risk to diseases and pests (Mefferd, 2017). Environment plays a key role in the successful growth of bell peppers and this research trial indicates that perhaps bell pepper production do not benefit from a high tunnel compared to the field in North Dakota.

CHAPTER 4: CUCUMBER

Introduction

Cucumber (*Cucumis sativus* L.) plants are frost-sensitive, warm-season annuals. The plants have a vining growth habit, square-shaped stems covered by stiff hairs, tendrils at each node that allow for growth on a support, long petioles, and rough, triangular-shaped leaves (Welbaum, 2015). The reproductive morphology can be monoecious (separate male and female flowers on the same plant), andromonoecious (separate perfect and male flowers on the same plant) or gynoecious (all female flowers on the plant) and is controlled genetically, but can be modified by environmental conditions and chemicals (Welbaum, 2015). Some genotypes may also have the ability to set fruit without pollination by an adaptation known as parthenocarpy (Mefferd, 2017).

In the Midwestern United States, high tunnels are primarily being used to extend the growing season of tomato (*Solanum lycopersicum* L.), because of the crop's high return on investment; growers are continuously cropping them, ultimately increasing disease and pest problems (Guan et al., 2019; Nennich and Wold-Burkness, 2012). Because of this, there is a need to provide cultivar recommendations for other profitable crops suitable for high tunnel rotation in the Midwest and Northern Great Plains. Behind tomato and pepper (*Capsicum annuum* L.), parthenocarpic cucumber is ranked third most important crop worldwide for high tunnel production (Lamont, 2009; Guan et al., 2019).

Because they are well adapted to trellising, cucumbers grown in a high tunnel have the unique advantage of exploiting the vertical space between the rafters and the ground (Guan et al., 2019; Shetty and Wehner, 1995). With the use of polyethylene twine suspended from the roof supports, vertically grown plants not only maximize the space efficiently, but reduce disease incidence by promoting good air flow between plants. Another advantage this provides, is the higher likelihood of longer, straighter more marketable fruit.

Cucumber cultivars have been developed over the years for many purposes, and as a result possess many different shapes and sizes. The differing cultivar characteristics broadly determine which category they fall into for their intended use (Welbaum, 2015). Fresh market cultivars usually have smoother, thicker skin and slightly tapered ends. The fruit is darker green in color and has a length-to-width ratio of 6:1. Generally the seed cavity will be larger than that of a processing cultivar. Processing cultivars are those having smaller fruits (about 3:1 length-to-width), thinner skins with more noticeable warts and blockier in shape. Cucumbers that are generally grown for fresh market use include the American slicing, the English or European, Oriental, Armenian and novelty types. Pickling cucumbers are normally grown for the processing market because they have special adaptations making them suitable for processing in vinegar to make products like pickles and relish; however they can be used as a fresh market product as well.

When choosing cultivars for high tunnel production, parthenocarpic and/or gynoecious varieties should be chosen to avoid pollination issues (Reid and Ivy, 2015). There are four major types of parthenocarpic cucumbers for fresh market consumption: Beit alpha or middle-eastern slicers, Dutch greenhouse, American slicer and Oriental (Shetty and Wehner, 1998; Guan et al., 2019). Developed in Israel to be parthenocarpic and gynoecious, the ‘Beit Alpha’ or ‘Beta Alpha’ cucumber is a popular choice for high tunnel growers. This seedless, dark-green hybrid is characterized by 13-18 cm smooth-skinned fruit and the potential for high yields due to multiple fruit per node and the ability to grow well in a wide range of temperatures both high (30-40°C) and low (10-15°C) (Guan et al., 2019; Welbaum, 2015). Dutch greenhouse cucumbers are characterized by their long (more than 28 cm), thin-skinned fruit having longitudinal ridges and are only cultivated in greenhouses. The thin-skinned fruit are shrink wrapped to prevent desiccation. The American slicer cucumbers were bred to have a long shelf-life which aided in long-distance shipping and are characterized by thick, dark-green skin. The last of the major parthenocarpic cucumbers is the oriental type which is sub-divided into North Chinese, South Chinese and Japanese types. The Japanese type is a cross between the North and South Chinese types and are characterized as having the greatest length to diameter ratio.

High tunnel environments are conducive to many disease and insect outbreaks. The predominant pest problem reported by high tunnel cucumber growers is the two-spotted spider mite (TSSM) (Guan et al., 2019; Ingwell et al., 2018; Lamont et al., 2003). Spider mite population growth is favored by hot, dry conditions, going from egg to adult in as little as 5 days (Jones et al., 2014). Little information is known about cucumber cultivar resistance to TSSM under high tunnel production, with limited availability of miticides for use in high tunnels (Guan et al., 2019).

The objectives of this trial were to evaluate nine commercially available cucumber cultivars in two locations representing eastern and western North Dakota to be conducted in side-by-side trials of outdoor field and indoor high tunnel production.

Methods and Materials

Site Description. The experiment was conducted in 2016 and 2017 at two separate locations in North Dakota representing the east and west climatic regions of the state within the NGP. The western location was at the NDSU Williston Research Extension Center (WREC) Nesson Valley Irrigation Research and Development Project (48°09’44.1” N and 103°06’29.7” W) near Williston, ND in Williams County (“NV”). This region in Norwest North Dakota is characterized by a semiarid climate with low humidity, frequent drying winds, low rainfall, abundant sunshine, hot summers and cold winters (Tollerud et al., 2018). Annual average precipitation is approximately 250 mm.

The eastern location was at the NDSU Dale E. Herman Research and Arboretum farm (46°59’28” N and 97°21’20” W) near Absaraka, ND (“ABS”) in Cass County. This region is characterized as having a continental climate, with hot or warm summers and cold winters with an average annual precipitation range between 380 and 760 mm (Tollerud et al., 2018). The total rainfall, daily maximum, and minimum air temperatures from May to September were recorded by North Dakota Agricultural Weather Network (NDAWN) for the two locations and years can be found in Appendix Figures A.3 and A.4.

Additional information on each location, high tunnel size and soil classification can be found in Appendix Table A.1. One high tunnel was constructed at each site in the fall of 2015 and completed in the spring of 2016. Both high tunnels (Northpoint, Rimol Greenhouse Systems, Inc. Hooksett, NH) were built in a north-south orientation with 13 gauge steel framework; double air inflated 4 year-rated 6 mil clear polyethylene greenhouse film treated with anti-condensate and ultraviolet features; and nominal lumber-framed end walls, baseboards and hip boards. Ventilation was accomplished by thermostatically controlled electric roll up sidewalls running the lengths of both sides set to open at 27°C, and motorized shutter vents in each gable end wall set to open at 21°C. Sidewalls were manually closed during high wind and storm events when deemed necessary.

Site Preparation. Prior to planting, each location collected soil cores to a depth of 30 cm and submitted them to the NDSU Soils Testing Lab (Fargo, ND) for a basic soil nutrient test (Appendix Table A.2.). The 2014 Midwest Vegetable Production Guide (Engel et al., 2014) was used for determining nutrient recommendations of N-P-K. A split application of N applied pre-plant, broadcasting granular 46% Urea fertilizer and incorporating it into soil, and the rest of the N was applied during the growing season as fruit development began. The post-planting fertilizer application used liquid 28% UAN injected into the irrigation system and applied to cucumbers as they were being drip-irrigated. Prior to planting, beds were tilled and formed using rotor-tiller equipment. All plantings were in single rows with one line of 15 mil drip tape (Toro® Aqua-Traxx, DripWorks, Willits, CA) with emitters spaced 20.3 cm on center with a 2.15 x 10^{-4} m^3/s flow rate that were installed after transplanting. The irrigation from planting until the end of June was scheduled on Monday, Wednesday and Friday. At the beginning of July, irrigation as reduced to twice a week for 5 hours. Weed management was accomplished using a 15-year, 3 oz. woven weed barrier (Agriculture Solutions, Strong, ME) laid on either side of the row and hand labor as needed.

Temperature. Weather data and soil temperatures were monitored in the field using the North Dakota Agricultural Weather Network (NDAWN). The NV location used the Hofflund Station located at 590 m elevation. The ABS location used the Prosper Station with an elevation of 284 m above sea level. The NDAWN station temperature and relative humidity sensors were set at 1.5 m from the soil surface. Soil temperature readings were taken at a depth of 10 cm (4-inch) for bare soil. A WatchDog 1000 series micro station (Spectrum Technologies, Inc. Aurora, IL) was used at the NV high tunnel to monitor air temperature, relative humidity and soil temperatures. A Decagon EM50 data logger (Decagon Devices, Inc., Pullman, WA) was set up at ABS to monitor inside and outside air temperature readings. Both data loggers were set up to be comparable to the NDAWN stations for air temperature.

Plant Materials. The high tunnels used for this trial also housed independent tomato, pepper, and cut flower cultivar trials for a total area of 232 m^2 under protection. For the indoor high tunnel trial (HT) and the outdoor field trial (FD), nine cucumber cultivars were selected (Johnny's Selected Seeds Winslow, ME). The cultivar names, recommended harvest length, days to maturity and cucumber type can be found in Table 4.1.

Table 4.1. Cucumber trial cultivars, seed source, days to maturity, harvest length, fruit type and market type (Johnny's Selected Seed, 2016).

Cultivar	Disease rating^y	Days to maturity^x	Harvest length cm	Cucumber type
Amiga F_1 ^{z}	CMV, PM, PRV, ZYMV. DM	55	15	Beit Alpha
Corinto F_1	CMV, CVYV, PM	48	19	American slicer
Diva	S. CVYV, DM, PM	58	15	Beit Alpha
Excelsior F_1	S, TSP. CMV, CVYC, PM	50	13	American Pickling
Harmonie F_1	PM, S. CMV	47	10	American Pickling
Iznik F_1	PM, S	45	10	Cocktail snack (mini)
Katrina F_1	S. CMV, CVYV, PM	49	15	Beit Alpha
Socrates F_1	S, TSP. PM	52	19	Beit Alpha
Tasty Jade F_1	DM, PM	54	29	Oriental

^{z} Refers to F_1 hybrid.
^{y} CMV=Cucumber Mosaic Virus, CVYV=Cucumber Vein Yellowing Virus, DM=Downy Mildew, PM=Powdery Mildew, PRV=Papaya Ringspot Virus, S=Scab, TSP=Target Spot, ZYMV=Zucchini Yellow Mosaic Virus.
^{x} Days to maturity is the days from transplant to first harvestable fruit.

Plant Establishment. In 2016, the cucumbers were direct seeded into the high tunnels 61 cm apart in single rows spaced 91 cm apart on 24 May at both locations. Two seeds per hill were planted; after germination one seedling was terminated. Each plant was pruned to one leader and grown vertically on outdoor trellising constructed of nominal lumber and fencing.

In 2017, transplants for ABS were seeded on 11 April in the North Dakota Agricultural Experiment Station (NDAES) greenhouses in Fargo, ND (20 ± 2°C, 16:8 L:D, RH = 40-65%). At NV 2017, transplants were seeded on the same date at WREC under indoor fluorescent lighting (40W Gro-Lux Wide Spectrum, Sylvania Ontario, Canada). Two seeds per SVD-450 molded plastic pot (T.O. Plastics, Clearwater, MN) were grown in growing medium (PRO-MIX

FLX, Premier Horticulture Inc., Quakertown, PA). Plants were not fertilized but watered with tap water once a week (100 mL).

After transplanting on 25 April at both locations on the same spacing as the previous year, one plant per hill was terminated. The remaining plant was later pruned and trellised to one leader that was suspended from the high tunnel rafters using tomahooks (Van den Wijngaart, The Netherlands) at the NV location, and Rollerhooks® (Paskal Technologies Agriculture, Israel) at the ABS location..

The field trial cucumbers were planted in an area adjacent to the high tunnels at both locations after the threat of a late spring frost had passed. At ABS, cucumbers were direct seeded on 24 May 2016 and 15 May 2017, and an outdoor trellis structure was constructed out of nominal lumber for the cucumbers in the field to grow on. At NV 2016, the field cucumbers were direct seeded on 2 June and grown on metal fencing; and in 2017, two week old transplants were planted into the field on 2 June and left to grow on the ground- similar to field cucumber production.

Data Collection. Harvest occurred weekly based on seed catalog recommendation for mature fruit lengths. Quality and marketability were assessed using the USDA Grading Standards for slicing (USDA, 2016) and pickling (USDA, 1936) cucumbers. Grades for slicers were U.S. Fancy (highest quality), U.S. No. 1 small, U.S. No. 1 large, and U.S. No. 2. The pickling grades were U.S. No. 1 (smallest in length), U.S. No. 2, and U.S. No. 3. The quality was based on shape, size, color, freshness, and surface defects. Total yield in kilograms per plant were based on harvest weights collected. Mean number of fruit were based on the total fruit harvested from each plant throughout the growing season. Mean fruit weights were calculated as the total yield divided by the total number of fruit harvested. Yields from inside the high tunnel were compared to those grown outside under field conditions, but were not statistically analyzed together. The percent marketable fruit were calculated as the difference between marketable and unmarketable fruit divided by the total and converted to a percentage.

Three of the cultivars included in this study were pickling cucumbers, Excelsior, Harmonie and Iznik, thus had been graded using USDA Grading Standards for pickles and the data was not consistent with that of the other cultivars graded using the USDA Grading Standard for slicing cucumbers. Therefore, only six cultivars Amiga, Corinto, Diva, Katrina, Socrates and Tasty Jade were statistically analyzed for marketability based on the grading standards for slicing cucumbers.

Two-spotted spider mite plant susceptibility was evaluated using the Horsfall-Barratt (Horsfall and Barratt, 1945) scale to rate leaf symptoms. In the current study, the nine cultivars were evaluated during the height of the infestation at the ABS location on 17 August 2017.

Experimental Design and Statistical Analysis

The trials were each planted in a randomized complete block design with four replications for a total of 20 m^2 trial area. The statistical analysis of data were performed using a linear model for SAS 9.4 (PROC GLIMMIX with the REML estimation method, SAS Institute, SAS Circle, Cary, NC) where cultivar and environments were considered fixed, and replications within environment were considered random effects. An environment was considered one experiment conducted at a specific location and a specific year. Mean separation was done through the PDIFF function standard error for a least significant difference calculation. An alpha level of $p < 0.05$ was used for all hypothesis tests. Data collected on disease incidence and insect infestation severity was analyzed for all cultivars. Homogeneity of variance was tested in marketability analysis using Levene's test.

Results and Discussion

High tunnel trial. Statistical analysis of the high tunnel study indicated highly significant differences for the main effects of cultivar and environment for average yield per plant in kilograms, but no cultivar by environment interaction. For average number of fruit harvested per plant and average fruit weight per plant, significant cultivar by environment interactions were found (Appendix Table A.7).

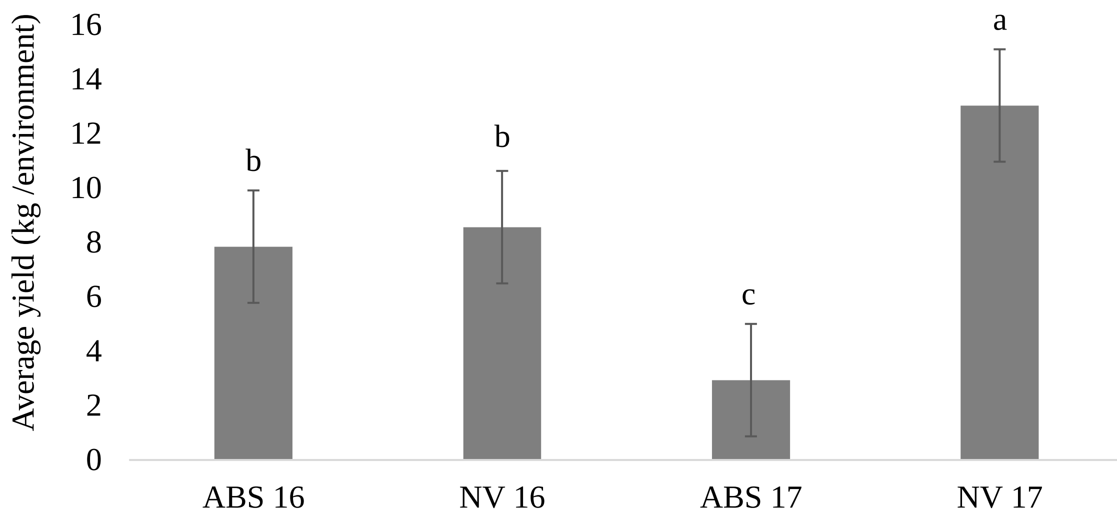

Figure 4.1. Average yield of cucumbers grown under high tunnel production at Absaraka and Nesson Valley, ND in 2016 and 2017. Means with a common letter are not significantly different at P<0.05 using Tukey's honestly significant difference test. SE bars indicate the mean ± 0.48 (n=4). ABS 16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017, NV17=Nesson Valley 2017.

The overall yield in kilograms per plant for the four environments indicated no statistical difference in yield between locations in the year 2016, while, there was a significantly lower yield at ABS and a significantly greater yield at NV in 2017 (Figure 4.1). Only plants in the 2017 NV environment exceeded 12 kg per plant.

Despite the yield differences due to environments, the cultivar Corinto came in as the top yielding cucumber in kg/plant over all experiments followed by ‘Tasty Jade’, although ‘Tasty Jade’ yield was not significantly different than ‘Iznik’, and ‘Socrates’ (Figure 4.2). The lowest yielding cultivar was Diva, but not significantly lower than cultivars, Amiga, Excelsior, Harmonie and Katrina. These findings are consistent with those of Pennsylvania State University researchers, Bogash et al., on their 2013 high tunnel trellised cucumber variety trial. Their top yielding cucumber was ‘Corinto’ and the lowest yielding was ‘Diva’. They also trialed the cultivars Socrates, which performed moderately well with fairly high yields, and Katrina which performed poorly due to reduced plant vigor according to their report.

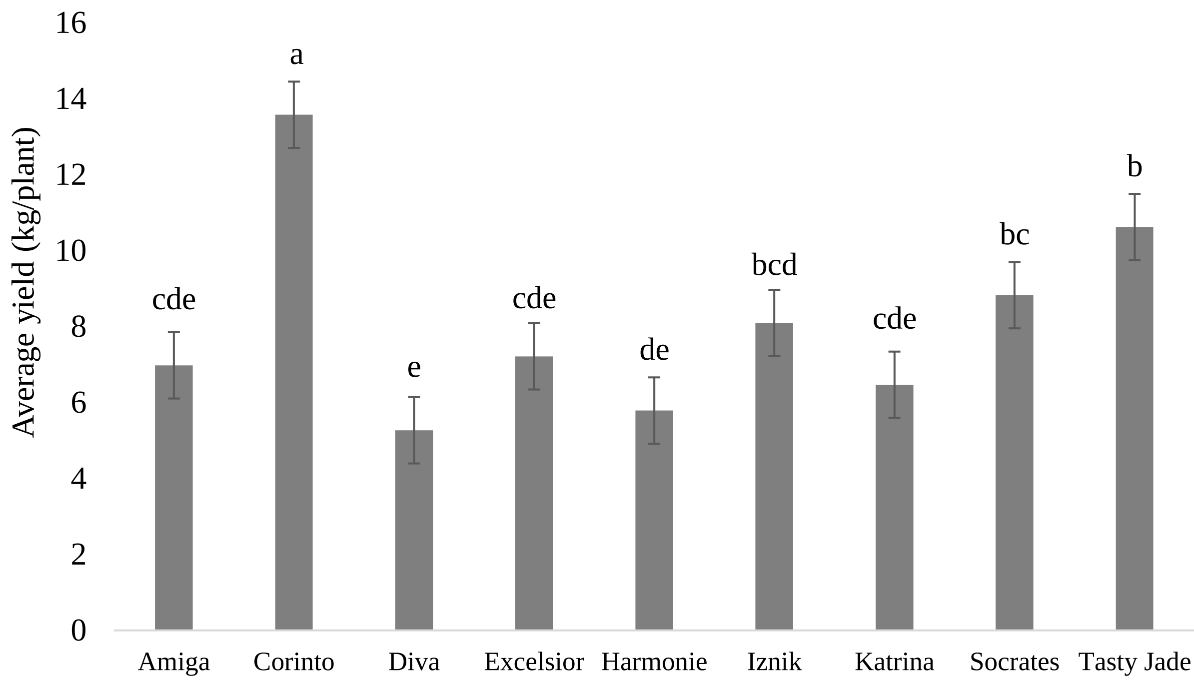

Figure. 4.2. Average yield of fruit harvested per plant in high tunnel trials conducted at Absaraka and Nesson Valley, ND in 2016 and 2017. Means followed by the same letters are not significantly different at $P<0.05$ using Tukey’s honestly significant difference test. SE bars indicate the mean ± 0.22 (n=4).

Initially, the environmental differences in cucumber yield were attributed to the fact that both high tunnels were constructed in the spring of 2016. Therefore, planting did not take place until late May and early June for both locations. Higher yields were expected for 2017 because of earlier planting dates. However, the ABS location reported high pest incidences in 2017, which attributed to the reduced yields. Attempts were made to eliminate the infestation initially by spraying the foliage with water to knock the insects down; then by repeated applications of diatomaceous earth; and finally by releasing a triple blend of biological predatory mites, *Phytoseiulus persimilis, Mesoseiulus longipes* and *Neoseiulus californicus* (Buglogical, Tucson, AZ) on 15 August. By then, however, the spider mite population was too high and uncontrollable through non-pesticide methods.

Due to a miscommunication, the reduced number of cucumbers from the 2017 ABS experiment was also attributable to changes made in the training and trellising techniques. The cucumber flowers at ABS were pinched back to encourage vegetative growth for initial vine training. By the time the plants were tall enough to allow fruit production, the onset of a foliar leaf disease appeared; followed by a spider mite infestation, all within a two-month period that ultimately reduced yields.

The Nesson Valley location experienced disease pressures from the high humidity high tunnel conditions. A foliar disease was noted late in the 2016 season, and a plant sample was sent to a plant diagnostics lab at North Dakota State University Fargo, ND. It was determined to be anthracnose *Colletotrichum orbiculare* (syn. *Colletotrichum lagenarium*), a fungal infection of cucurbits. There was also a spider mite infestation noted late in the season. In 2017, a fungicidal spray rotation was initiated as a preventative measure. Thrips (*Frankliniella occidents* Pergande) were noted in the early season, and insecticides were added to the rotation of weekly applications starting on 6 June and ending 4 August (Appendix Table A.9). A heavy infestation of spider mites began mid-season. Insecticide applications were discontinued and a biological predatory mite release on 11 September was attempted with little success.

Because of the cultivar by environment interaction on the average number of fruit harvested per plant (Appendix Table A.7), the data is sliced into cultivar-specific components. The resulting p-values indicate 'Amiga', 'Diva' and 'Tasty Jade' as having no evidence of difference in average number of fruit harvested over the four environments (Table 4.2). When the interaction is sliced by environment, the *F*-tests of cultivar differences within each environment indicate that there was a significant cultivar response to the NV locations.

Table 4.2. P-values for slices of the cultivar by environment interaction average number of fruit harvested per plant for cucumber cultivars grown in high tunnels at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar-specific tests		Environment-specific tests	
Cultivar	P-value[z]	Location, Year	P-value[y]
Amiga	0.0952	Absaraka, 2016	0.1898
Corinto	0.0067	Nesson Valley, 2016	<.0001
Diva	0.1801	Absaraka, 2017	0.993
Excelsior	<.0001	Nesson Valley, 2017	<.0001
Harmonie	<.0001		
Iznik	<.0001		
Katrina	0.0041		
Socrates	0.0068		
Tasty Jade	0.2533		

[z]Each cultivar specific test compares the average responses of a cultivar across four environments; each test has three numerator degrees of freedom.
[y]Each environment-specific test compares the average response of nine cultivars in the specified environment; each test has eight numerator degrees of freedom.

When sorted by experiment, the cultivar Excelsior produced more fruit than Amiga, Diva, Iznik, Katrina, Socrates, and Tasty Jade plants at ABS16 (Table 4.3). For NV16, 'Iznik' produced more fruit than any of the other cultivars. Cultivar fruit production varied in 2017 at both locations. For ABS17, the cultivars Corinto and Tasty Jade produced the greatest number of fruit, but this was only greater than fruit produced by Harmonie and Katrina. For NV17, the cultivar Excelsior produced more fruit than Amiga, Corinto, Diva, Katrina, Socrates, and Tasty Jade. Thus, for two environments, 'Excelsior' produced the greatest number of fruit, while for the other two environments, 'Iznik', 'Corinto', and 'Tasty Jade' produced the greatest number of fruit. In contrast, 'Diva' produced the fewest number of fruit for three of the four environments.

Table 4.3. Average number of fruit harvested per plant for cucumber cultivars grown in high tunnels at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

	ABS 16[z]		NV 16		ABS 17		NV 17	
Cultivar	---------------------------------- No./plant ----------------------------------							
Amiga	22	cd[y]	33	cd	15	ab	49	c
Corinto	47	ab	42	bc	18	a	70	bc
Diva	13	d	17	d	10	bcd	39	c
Excelsior	52	a	29	cd	13	abc	113	a
Harmonie	34	bc	59	b	7	cd	76	abc
Iznik	26	cd	97	a	12	abc	101	ab
Katrina	29	cd	25	cd	5	d	59	c
Socrates	27	cd	34	cd	12	abc	62	c
Tasty Jade	31	bc	23	cd	17	ab	44	c

[z] ABS16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017.
[y] Within a column, means followed by the same letters are not significantly different at P<0.05 using Tukey's honestly significant difference test (n=4).

Table 4.4. P-values for slices of the cultivar by environment interaction average number of fruit harvested per plant for cucumber cultivars grown in high tunnels at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar-specific tests		Environment-specific tests	
Cultivar	P-value[z]	Location, Year	P-value[y]
Amiga	0.0015	Absaraka, 2016	<.0001
Corinto	0.1545	Nesson Valley, 2016	<.0001
Diva	0.0006	Absaraka, 2017	<.0001
Excelsior	0.0231	Nesson Valley, 2017	<.0001
Harmonie	0.1578		
Iznik	<.0001		
Katrina	0.0007		
Socrates	0.4825		
Tasty Jade	0.0101		

[z]Each cultivar specific test compares the average responses of a cultivar across four environments; each test has three numerator degrees of freedom.
[y]Each environment-specific test compares the average response of nine cultivars in the specified environment; each test has eight numerator degrees of freedom.

If the average fruit weight in grams cultivar by environment interaction is sliced into cultivar-specific components, the resulting p-values indicate 'Corinto', 'Harmonie' and 'Socrates' as having no evidence of difference in mean fruit weight harvested over the four environments (Table 4.4). When the interaction is sliced by environment, the *F*-tests of cultivar differences within each environment indicate that there was a significant cultivar response to all four environments.

For the average fruit weight per plant in grams, ‘Tasty Jade’ produced statistically heavier fruit in all environments with the exception of ABS 2017 where its fruit weight did not differ from ‘Corinto’ and ‘Diva’ (Table 4.5). The recommended fruit harvest length for ‘Tasty Jade’ was 28-30 cm. The cultivars that produced the smallest cucumbers on average were the pickling cucumbers Excelsior, Harmonie, and Iznik with the recommended fruit harvest length of 10 cm each. Two of the three cultivars statistically had the lightest fruit in all four environments.

Table 4.5. Average fruit weight per plant for cucumber cultivars grown in high tunnels at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

	ABS 16[z]		NV16		ABS17		NV17	
Cultivar	----------------------- fruit weight (g) ------------------------							
Amiga	308.4	b[y]	214.6	d	228.4	bc	224.6	cd
Corinto	310.8	b	344.2	b	316.7	a	284.2	b
Diva	310.3	b	324.2	bc	267.6	ab	221.7	cd
Excelsior	149.6	d	178.8	de	195.0	cd	118.9	e
Harmonie	133.2	d	157.7	ef	101.9	e	113.2	e
Iznik	240.3	c	120.0	f	154.5	de	119.0	e
Katrina	293.3	b	218.8	d	207.5	bcd	188.5	d
Socrates	280.5	b	278.7	c	252.4	bc	249.1	bc
Tasty Jade	374.0	a	403.2	a	316.2	a	351.5	a

[z] ABS16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017.
[y] Within a column, means followed by the same letters are not significantly different at P<0.05 using Tukey’s honestly significant difference test (n=4).

The assessment of fruit quality was based on the USDA Grading Standards for slicing cucumbers in which each fruit harvested was placed into a grading category US Fancy, US No 1 and US No 2 upon harvest. Subjective by nature in that quality is very much visual and the perception of appearance and fruit characteristic varies from person to person; the fruit quality assessment was gathered at NV, the location where the researcher was present. The overall marketability was determined by a percentage of the total number of cucumbers harvested and the total number of cucumbers that fell into either US Grade Fancy, US No 1 or US No 2. The cultivar Tasty Jade produced the greatest percentage of marketable fruit at 78%, though not statistically different than the cultivars Amiga, Corinto and Diva (Figure 4.3). The cultivar Socrates produced the lowest percentage of marketable fruit at 57%, but was not statistically different than the cultivars Katrina, Amiga and Diva. Although minimal statistical significance was found between all cultivars in this case, a grower may wish to know which varieties produce the most marketable fruit for economic purposes.

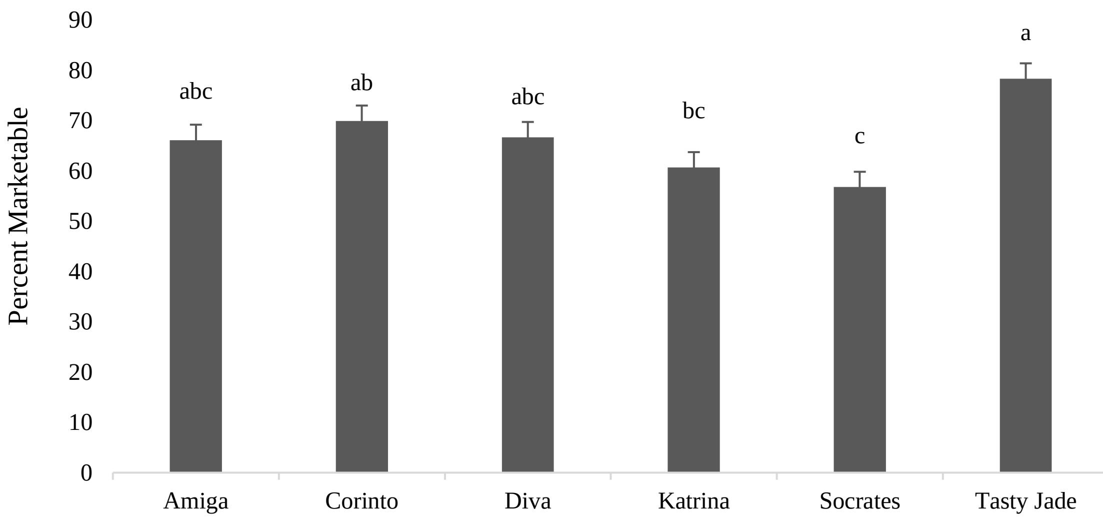

Figure 4.3. Percentage of marketable cucumber fruit per cultivar harvested from high tunnel trials at Nesson Valley, ND in 2016 and 2017. Means followed by the same letters are not significantly different at P<0.05 using Tukey's honestly significant difference test. SE bars indicate the mean ± 2.62 (n=4).

Of those fruit that were marketable, the cultivar that produced the most US Fancy cucumbers was Corinto followed by Tasty Jade, though not statistically different than one another (Figure 4.4).

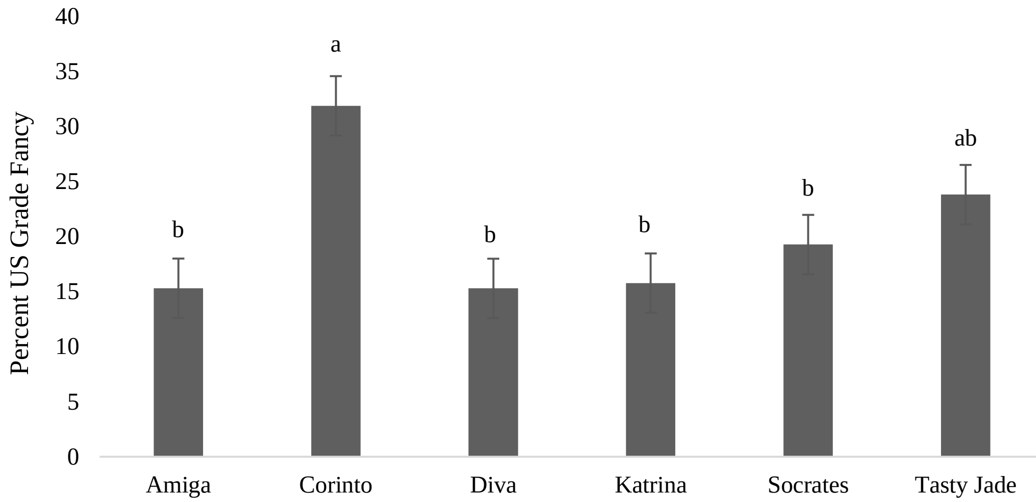

Figure 4.4. Percentage of cucumber fruit graded U.S. Fancy grown under high tunnel at Nesson Valley, ND in 2016 and 2017. Means followed by the same letters are not significantly different at P<0.05 using Tukey's honestly significant difference test. SE bars indicate the mean ± 2.34 (n=4).

Two-spotted spider mite resistance among cucumber cultivars has been comparatively examined in previous greenhouse studies (Maleknia et al., 2016). However, little is known about two-spotted spider mite resistance in high tunnel cucumber production (Guan et al., 2019). In the current study, it was observed that the cultivar Harmonie experienced the most leaf damage caused by two-spotted spider mites compared to the other cultivars, but was not significantly different than Katrina and Diva (Table 4.6). The cultivar Corinto had the least amount of leaf damage, but was not statistically different that Tasty Jade, Excelsior, Amiga, Socrates and Iznik. The results correlate well with the study conducted by Guan et al., 2019 in which researchers concluded that Japanese cultivars were more tolerant to two-spotted spider mite damage as compared to other types, Dutch greenhouse, and Beit alpha and American slicer. They cited cultivars Taurus, Tasty Jade and Tasty Green as Japanese type cucumbers included in their trial. Their study also included the cultivars Katrina and Socrates which scored a 7.0 and 4.7, respectively on the Horsfall-Barratt rating scale.

Table 4.6. Susceptibility of cucumber cultivars to two-spotted spider mites during the cucumber cultivar trial conducted in the high tunnel at Absaraka, ND in 2017.

Cultivar	Rating[z]	
Amiga	8.0	c[y]
Corinto	7.6	c
Diva	9.6	ab
Excelsior	8.0	c
Harmonie	10.6	a
Iznik	8.8	bc
Katrina	10.6	a
Socrates	8.1	bc
Tasty Jade	7.8	c

[z]Severity of plant leaf damage caused by two-spotted spider mites was evaluated using the Horsfall-Barratt rating scale on 17 August. The percentages of leaf area that showed visual cell damage and had two-spotted spider mites on the leaves were recorded. Horsfall Barratt rating scale: 1=0% leaf symptoms; 2 = 0-3%; 3 = 3-6%; 4 = 6-12%; 5 = 12-25%; 6 = 25-50%; 7 = 50-75%; 8 = 75-88%; 9 = 88-94%; 10 = 94-97%; 11 = 97-100%; 12 = 100% (Horsfall and Barratt, 1945).

[y]Within a column means followed by the same letter are not significantly different at $P<0.05$ using Tukey's honestly significant difference test (n=4).

Field trial. The field trials were subjected to all weather conditions including but not limited to wind and heavy rains. The evaporative demand is greater in the western region of the state compared to other parts of the state. The western region potential evapotranspiration rate is 125 mm greater than the eastern region, but having 150 mm less rainfall (Staricka, 2020). The significant interaction effect of cultivar by experiment for yield in kg/plant, total fruit harvested per plant, and mean fruit weight in grams was the result of the high degree of variability found among field trials (Appendix Table A.8).

Because of the difference found in the cultivar by environment interactions on the total yield (kg/plant), the total number of fruit harvested per plant and the mean fruit weight (Table A.8), the data is sliced by into cultivar-specific components for each. The resulting p-values indicate 'Harmonie' as the only cultivar to show no evidence of difference in mean total yield of fruit harvested over the four environments (Table 4.7). When the interaction is sliced by environment, the *F*-tests of cultivar differences within each environment indicate that there was a significant cultivar response to ABS16.

Table 4.7. P-values for slices of the cultivar by environment interaction average yield harvested per plant from cucumbers grown in the field at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar-specific tests		Environment-specific tests	
Cultivar	P-value[z]	Location, Year	P-value[y]
Amiga	0.0054	Absaraka, 2016	<.0001
Corinto	<.0001	Nesson Valley, 2016	0.8907
Diva	0.0302	Absaraka, 2017	0.9999
Excelsior	0.0039	Nesson Valley, 2017	0.2241
Harmonie	0.1425		
Iznik	0.0107		
Katrina	0.0025		
Socrates	0.0081		
Tasty Jade	<.0001		

[z]Each cultivar specific test compares the average responses of a cultivar across four environments; each test has three numerator degrees of freedom.

[y]Each environment-specific test compares the average response of nine cultivars in the specified environment; each test has eight numerator degrees of freedom.

When sorted by experiment, the cultivar Corinto produced the greatest yield than any of the other cultivars at ABS16 (Table 4.8). At NV16, 'Socrates' produced the greatest yield but not statistically more than the cultivar Excelsior. In 2017, the cultivar Tasty Jade produced the greatest yield, but this was only greater than fruit produced by 'Harmonie'. For NV17, the cultivar Tasty Jade also produced greater yield, but only statistically more than Excelsior, Harmonie, Iznik and Katrina. Thus, for two environments in 2017, 'Tasty Jade' produced the greatest yield.

Table 4.8. Average yield harvested per plant from cucumbers grown in the field at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

	ABS 16[z]		NV 16		ABS 17		NV 17	
Cultivar	kg/plant							
Amiga	6.2	bc[y]	1.4	cd	0.7	abc	6.8	ab
Corinto	19.1	a	1.9	bcd	1.2	ab	5.1	abc
Diva	3.7	c	2.0	bcd	0.8	abc	7.6	ab
Excelsior	8.6	bc	3.1	ab	0.8	abc	3.5	c
Harmonie	4.9	c	1.9	bcd	0.3	c	3.7	c
Iznik	7.7	bc	2.0	bcd	1.0	ab	3.3	c
Katrina	8.5	bc	2.5	bc	0.6	bc	4.7	bc
Socrates	8.0	bc	4.4	a	1.2	ab	7.1	ab
Tasty Jade	12.1	b	1.0	d	1.4	a	7.8	a

[z] ABS16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017, NV17=Nesson Valley 2017.

[y]Within a column means followed by the same letter are not significantly different at $P<0.05$ using Tukey's honestly significant difference test (n=4).

When the number of fruit harvested cultivar by environment interaction is sliced, the resulting p-values indicate 'Socrates' as the only cultivar to show no evidence of difference in mean total number of fruit harvested over the four environments (Table 4.9). When sliced by environment, the *p*-values indicate that there was a significant cultivar response to ABS16.

Table 4.9. P-values for slices of the cultivar by environment interaction average number of fruit harvested per plant for cucumber cultivars grown in field trials at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar-specific tests		Environment-specific tests	
Cultivar	P-value[z]	Location, Year	P-value[y]
Amiga	0.0073	Absaraka, 2016	<.0001
Corinto	<.0001	Nesson Valley, 2016	0.625
Diva	0.01	Absaraka, 2017	1
Excelsior	<.0001	Nesson Valley, 2017	0.5918
Harmonie	0.0001		
Iznik	0.0002		
Katrina	0.0228		
Socrates	0.0513		
Tasty Jade	0.0199		

[z]Each cultivar specific test compares the average responses of a cultivar across four environments; each test has three numerator degrees of freedom.
[y]Each environment-specific test compares the average response of nine cultivars in the specified environment; each test has eight numerator degrees of freedom.

The average number of fruit produced by a cultivar separated by experiments did not coincide with yield results. At ABS in 2016, the three pickling cultivars Excelsior, Harmonie, and Iznik along with Corinto produced the most fruit, but only Excelsior produced more fruit than all except Corinto (Table 4.10). At NV16, the three pickling cultivars along with Socrates produced the most fruit, but only Excelsior produced ore fruit than all except Socrates. At ABS in 2017, the number of fruit was drastically less and all cultivars produced a similar number of fruit. At NV in 2016, the cultivars all produced similar number of fruit except for 'Corinto' which produced statistically less than cultivars Amiga, Diva, Excelsior and Iznik.

Table 4.10. Average number of fruit harvested per plant for cucumber cultivars grown in field trials at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

	ABS 16[z]		NV 16		ABS 17		NV 17	
Cultivar	---------------------------- No./plant ----------------------------							
Amiga	20	cd[y]	8	cde	4	abc	38	a
Corinto	54	ab	7	de	5	ab	23	b
Diva	11	d	8	cde	3	bc	40	a
Excelsior	83	a	25	a	5	ab	44	a
Harmonie	48	bc	15	bc	3	c	36	ab
Iznik	46	bc	15	bc	5	abc	42	a
Katrina	30	bcd	11	cd	3	abc	31	ab
Socrates	27	bcd	19	ab	5	a	34	ab
Tasty Jade	32	bcd	4	e	5	a	27	ab

[z] ABS16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017, NV17=Nesson Valley 2017.
[y]Within a column means followed by the same letter are not significantly different at P<0.05 using Tukey's honestly significant difference test (n=4).

When the cultivar by environment interaction for average fruit weight is sliced, the resulting p-values indicate 'Excelsior', 'Harmonie' and 'Socrates' as the cultivars to show no evidence of difference in average fruit weight harvested over the four environments (Table 4.11). When sliced by environment, the *p*-values indicate that there was a significant cultivar response to all locations.

Table 4.11. P-values for slices of the cultivar by environment interaction average fruit weight harvested per plant for cucumber cultivar trials grown in field trials at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

Cultivar-specific tests		Environment-specific tests	
Cultivar	P-value	Location, Year	P-value
Amiga	0.001	Absaraka, 2016	<.0001
Corinto	0.0051	Nesson Valley, 2016	0.0012
Diva	0.0434	Absaraka, 2017	0.0143
Excelsior	0.0525	Nesson Valley, 2017	<.0001
Harmonie	0.4195		
Iznik	0.0027		
Katrina	0.0071		
Socrates	0.1303		
Tasty Jade	0.006		

Each cultivar specific test compares the average responses of a cultivar across four environments; each test has three numerator degrees of freedom
Each environment-specific test compares the average response of nine cultivars in the specified environment; each test has eight numerator degrees of freedom.

The longer fruit for 'Tasty Jade' and shorter fruit for the three pickling cultivars (Excelsior, Harmonie, and Iznik) suggested that these cultivars would produce the heaviest and lightest fruit. However, this only occurred at NV in 2017 (Table 4.12). At ABS in 2016, the cultivars Corinto and Tasty Jade produced heavier fruit than all other cultivars, while Excelsior and Harmonie produced the lightest fruit. At NV in 2016, the cultivars Corinto, Diva, Katrina, Socrates, and Tasty Jade produced the heaviest fruit, but this was only heavier than the fruit from Excelsior. At ABS 16 the cultivar Amiga produced the heaviest fruit but was only statistically heavier than Harmonie. As expected, 'Tasty Jade' produced heavier fruit than all the other cultivars at ABS 16 and NV 17, but was surpassed by Diva in NV 16 and ABS 17.

Table 4.12. Average fruit weight harvested per plant from field cucumber trial conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

	ABS 16[z]		NV 16		ABS 17		NV 17	
Cultivar	weight (g)							
Amiga	305.58	b[y]	184.52	ab	289.9	a	181.87	cd
Corinto	349.98	a	239.23	a	237.92	abc	224.96	b
Diva	307.05	b	259.7	a	270.37	ab	186.86	bcd
Excelsior	105.18	d	119.35	c	181.55	bc	75.45	e
Harmonie	88.35	d	128.92	bc	148.25	c	102.69	e
Iznik	168.88	c	141.8	bc	227.92	abc	79.54	e
Katrina	289.43	b	222.53	a	225.73	abc	150.99	d
Socrates	292.73	b	225.32	a	243.32	abc	203.35	bc
Tasty Jade	375.93	a	245.4	a	263.03	ab	281.79	a

[z] ABS16=Absaraka 2016, NV16=Nesson Valley 2016, ABS17=Absaraka 2017, NV17=Nesson Valley 2017.
[y]Within a column means followed by the same letter are not significantly different at $P<0.05$ using Tukey's honestly significant difference test (n=4).

Conclusion

Trials were conducted to examine the behavior of nine commercially available cucumber cultivars grown under two very different environments, high tunnel and field, at two locations in the Northern Great Plains over two growing seasons. The cultivars Corinto, Diva, Katrina, Socrates and Tasty Jade were specifically marketed as having an adaptation that made them suitable for both protected culture and field production. Those adaptations include slightly thicker skin, parthenocarpy, and the ability to withstand higher temperatures. Of those cultivars, only Corinto and Diva were both said to be gynoecious - that is having a higher percentage of female flowers. However, as the yield results indicate, 'Corinto' appeared to be the most adapted and 'Diva' appeared to be the least adapted to high tunnel production in North Dakota. Perhaps 'Diva' required higher temperatures than what our northern latitude produced.

The cultivar Amiga was said to be an improved Beit Alpha field cucumber having spineless, thin skin of dark green color. Having thin skin always leaves room for the potential for damage from post-harvest handling and also pest damage. And while it didn't perform the poorest in the high tunnel trials, it certainly did not outperform the other selections in the field, either.

The recommended harvest length for the cultivar Tasty Jade was 29 cm. This was, on average, twice the recommended harvest lengths for the other cultivars. This harvest length undoubtedly influenced the yield per plant, number of fruit harvested, and average fruit weight. In the same respect, the cultivars Excelsior, Harmonie and Iznik were recommended as pickling cucumbers and thus harvested at 8 cm or less. This influenced the yield per plant, number of fruit harvested and average fruit weight from these three cultivars over the others.

Some of the cultivar yield differences could be attributed to environmental differences. However, training and trellising changes occurred the second year at both locations, which may have influenced cultivar yields. In the field at NV 16, welded wire mesh was set up for the vines to grow vertically after germination and the plants were pruned to one leader. In 2017, the robust two-week old transplants were left to sprawl along the ground and only pruned as needed. The average monthly temperatures from April to September in both growing seasons were comparable to one another. The disease and pest pressures in the field were minimal.

In the ABS field trial, a nearly ten-fold reduction in production occurred from 2016 to 2017. At the discretion of the staff at that location, it was decided that the flowers should be pruned to encourage initial vegetative growth while training of the vines was taking place. This, coupled with cooler soil temperatures, which resulted in slow germination of the seeds, and the overall weather patterns ultimately proved detrimental to the 2017 cucumber field production at ABS.

Despite the higher pest incidence experienced in the high tunnels, yields were increased by 1.9 times over the field trials, and 1.7 times more cucumbers were harvested. The high tunnels lengthened the season on average by 27 days and increased the harvest window by approximately nine weeks. The results of this study demonstrates excellent cucumber production potential for high tunnels in the NGP.

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APPENDIX

Table A.1. Location, high tunnel dimensions, soil series†, taxonomy and slope of high tunnel experiments conducted in 2016 and 2017.

Location	Size	Soil Series	Taxonomy	% Slope
Williams County	7.9m x 29.3m	Bowdle-Lehr	Loam	0-2
Cass County	9.1m x 29.3m	Warsing	Sandy loam	0-2

†Soil data obtained from USDA-NRCS Web Soil Survey, 2017.

Table. A.2. Soil test results taken at Absaraka and Nesson Valley spring 2016 and 2017.

2016		NO^3-N	P	K		EC	OM
Location	Trial	lbs/A	ppm	ppm	pH	Mmhos/cm	%
Absaraka	High tunnel	13	28	204	6.8	--	--
Absaraka	Field	11	28	178	7.1	--	--
Nesson Valley	High tunnel	8	7	173	7.0	0.21	2.8
Nesson Valley	Field	8	6	150	7.1	0.25	2.7
2017							
Absaraka	High tunnel	31	33	172	7.1	0.22	1.5
Absaraka	Field	10	27	136	6.8	0.16	1.6
Nesson Valley	High tunnel	74	4	142	7.1	0.55	2.5
Nesson Valley	Field	19	4	142	7.1	0.27	2.8

Table A.3. Analysis of variance for response variables average plant yield, average number of fruit per plant and average fruit weight per plant for high tunnel tomato trial conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

		ANOVA		
		Avg. yield/plant (kg)	Avg. number of fruit/plant	Average fruit weight (g)
Effect	df	---------- Probability > F -----------		
Environment	2	0.0076	<.0001	<.0001
Rep (environment)	9	--	--	--
Cultivar	7	0.0105	<.0001	<.0001
Cultivar * environment	14	0.0306	0.0897	<.0001

Table A.4 Analysis of variance for response variables average plant yield, average number of fruit per plant and average fruit weight per plant for field tomato trial conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

ANOVA				
		Avg. yield/plant (kg)	Avg. number of fruit/plant	Average fruit weight (g)
Effect	df	----------------- Probability > F	-----------------	
Environment	3	<.0001	<.0001	<.0001
Rep (environment)	12	--	--	--
Cultivar	7	0.0428	<.0001	<.0001
Cultivar * environment	14	0.2559	0.02	<.0001

Table A.5. Analysis of variance for response variables average plant yield, average number of fruit per plant and average fruit weight per plant for high tunnel pepper trial conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

ANOVA				
		Avg. yield/plant (kg)	Avg. number of fruit/plant	Average fruit weight (g)
Effect	df	-------------------- Probability > F	--------------------	
Environment	3	<.0001	<.0001	<.0001
Rep (environment)	12	--	--	--
Cultivar	7	0.6006	<.0001	<.0001
Cultivar * environment	21	0.4338	<0.001	<.0001

Table A.6. Analysis of variance for response variables average plant yield, average number of fruit per plant and average fruit weight per plant for field pepper trial conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

ANOVA				
		Avg. yield/plant (kg)	Avg. number of fruit/plant	Average fruit weight (g)
Effect	df	---------- Probability > F	-----------	
Environment	3	<0.001	<.0001	0.0003
Rep (environment)	12	--	--	--
Cultivar	7	0.7312	<.0001	<.0001
Cultivar * environment	21	0.9026	0.0657	0.1365

Table A.7. Analysis of variance for response variables average plant yield, average number of fruit per plant and average fruit weight per plant for high tunnel cucumber trial conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

ANOVA				
		Avg. yield/plant (kg)	Avg. number of fruit/plant	Average fruit weight (g)
Effect	df	---------- Probability > F -----------		
Environment	3	<.0001	<.0001	<.0001
Rep (environment)	12	--	--	--
Cultivar	8	<.0001	<.0001	0.0019
Cultivar * environment	24	0.7429	0.001	<.0001

Table A.8. Analysis of variance for response variables average yield, average number of fruit and average fruit weight for field cucumber trial conducted at Absaraka and Nesson Valley, North Dakota in 2016 and 2017.

ANOVA				
		Avg. yield/plant (kg)	Avg. number of fruit/plant	Average fruit weight (g)
Effect	df	---------- Probability > F -----------		
Environment	3	<.0001	<.0001	0.0001
Rep (environment)	12	--	--	--
Cultivar	8	0.0075	0.0011	<.0001
Cultivar * environment	24	0.0002	0.009	0.024

Table A.9. Product name, manufacturer, common name, rate and date of application of fungicide and insecticides applied in high tunnel and field experiments NV 2017.

Product name	Company	EPA reg. number	Rate applied[z]	Date	Location applied[y]	Insect or disease
Mustang Maxx	FMC Corp., Philadelphia, PA	279-3426	4.0 fl oz/A	9 June	HT / FD	thrips
Bravo Weatherstik	Syngenta, Greensboro, NC	50534-188-100	1.5 pt/A: P. 2 pt/A: T. & C.	9 June	HT / FD	foliar fungicide
Mustang Maxx	FMC Corp., Philadelphia, PA	279-3426	4.0 fl oz/A	15 June	HT	thrips
Quadris	Syngenta, Greensboro, NC	100-1098	15.5 oz/A: C. & P. 6.2oz/A: T.	19 June	HT / FD	foliar fungicide
Baythroid XL	BASF Corp., Research Triangle Park, NC	264-840	2.8 fl oz/A	21 June	HT / FD	thrips
Actinovate SP	Novozymes BioAg Inc. Brookfield, WI	73314-1	12 fl. oz./A	26 June	HT	biological fungicide
Mustang Maxx	FMC Corp., Philadelphia, PA	279-3426	4.0 fl oz/A	27 June	HT / FD	thrips
Bravo Weatherstik	Syngenta, Greensboro, NC	50534-188-100	2 pt/A	27 June	HT / FD	foliar fungicide
Neem Oil	Lawn and Garden Products INC	70051-2-54705	3 fl oz/gal	30 June	HT	green peach aphid
Neem Oil	Lawn and Garden Products INC	70051-2-54705	3 fl oz/gal	7 July	HT	green peach aphid
Bravo WeatherStik	Syngenta, Greensboro, NC	50534-188-100	2 pt/A	7 July	HT / FD	foliar fungicide
Malathion	Ortho, Marysville, OH	239-739	3 tsp/gal P.	12 July	HT	green peach aphid
Bravo Weatherstik	Syngenta, Greensboro, NC	50534-188-100	2 pt/A	21 July	HT / FD	foliar fungicide
Malathion	Ortho, Marysville, OH	239-739	3 tsp/gal P. & T.	21 July	HT	green peach aphid
Manzate + Endura	Dupont and BASF	352-706 & 7969-197	1.25qt/A 3.5oz/A	27 July	HT / FD	foliar fungicide
Neem Oil	Lawn and Garden Products INC	70051-2-54705	3 fl. oz./gal P.	4 August	HT	green peach aphid

[z] C=cucumber, P=pepper, T=tomato.
[y]HT=High Tunnel, FD=Field.

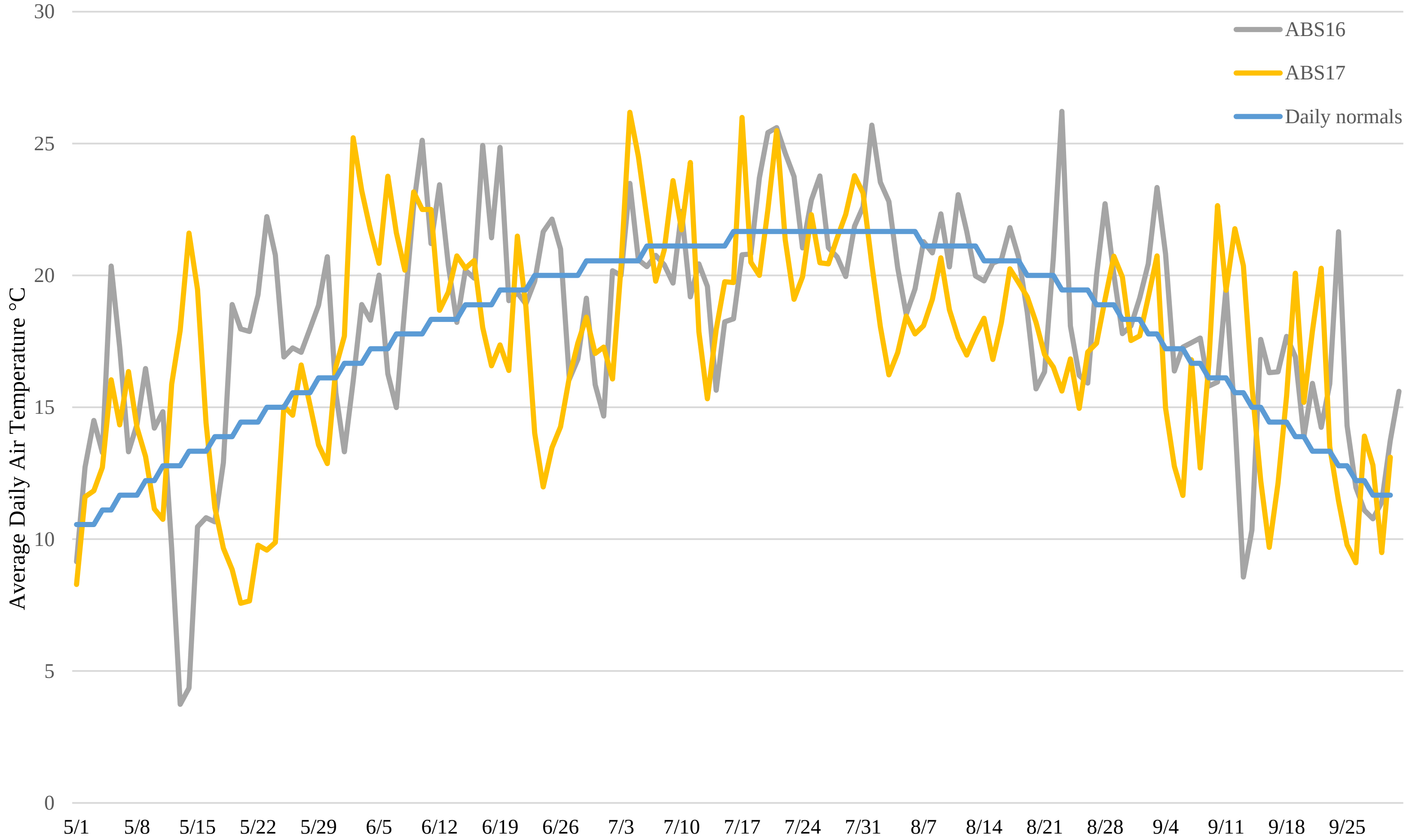

Figure A.1. Departure from normals recorded at Absaraka, ND from May-September 2016 and 2017.

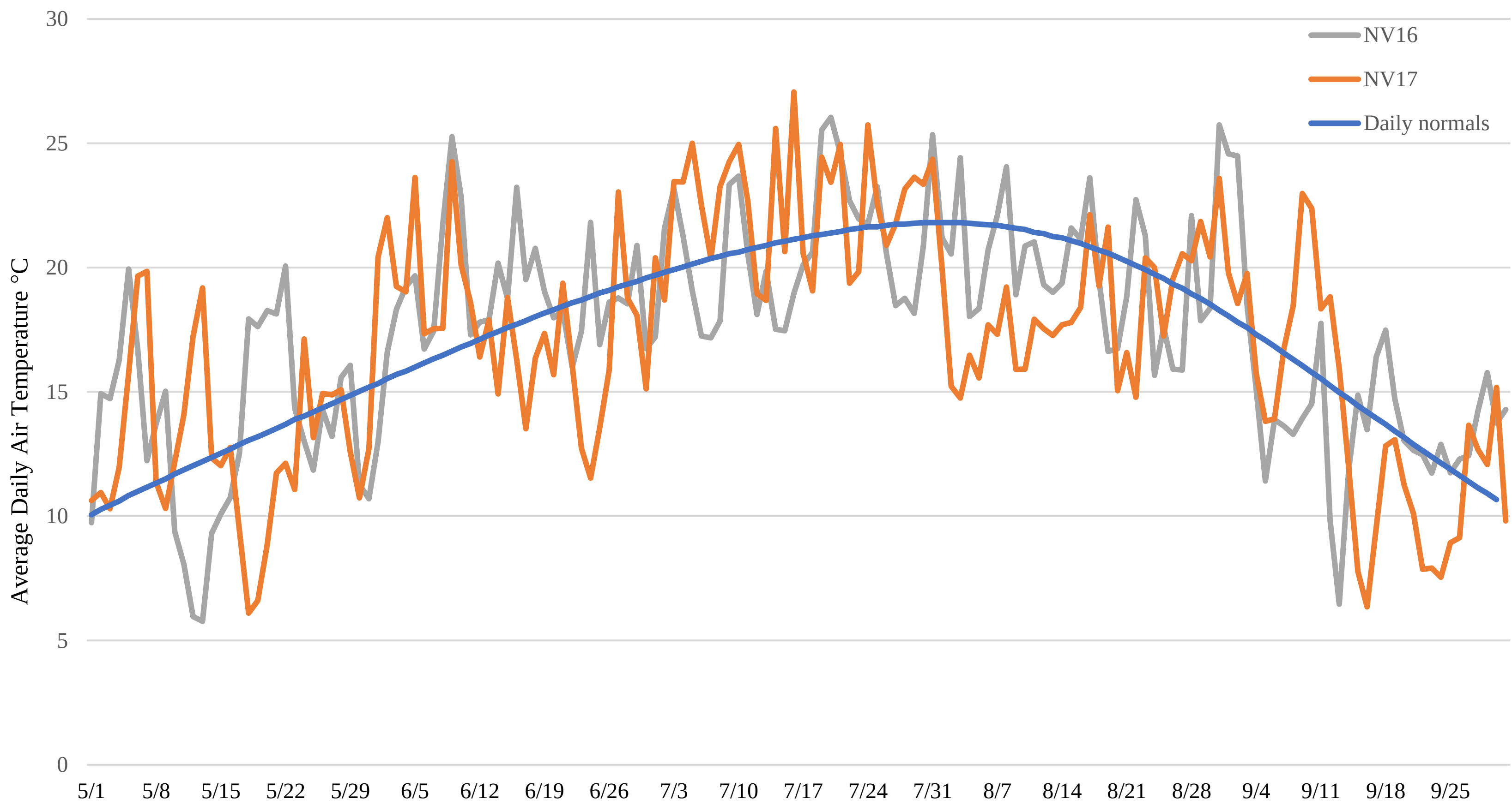

Figure A.2. Departure from normals recorded at Nesson Valley, ND from May - September 2016 and 2017

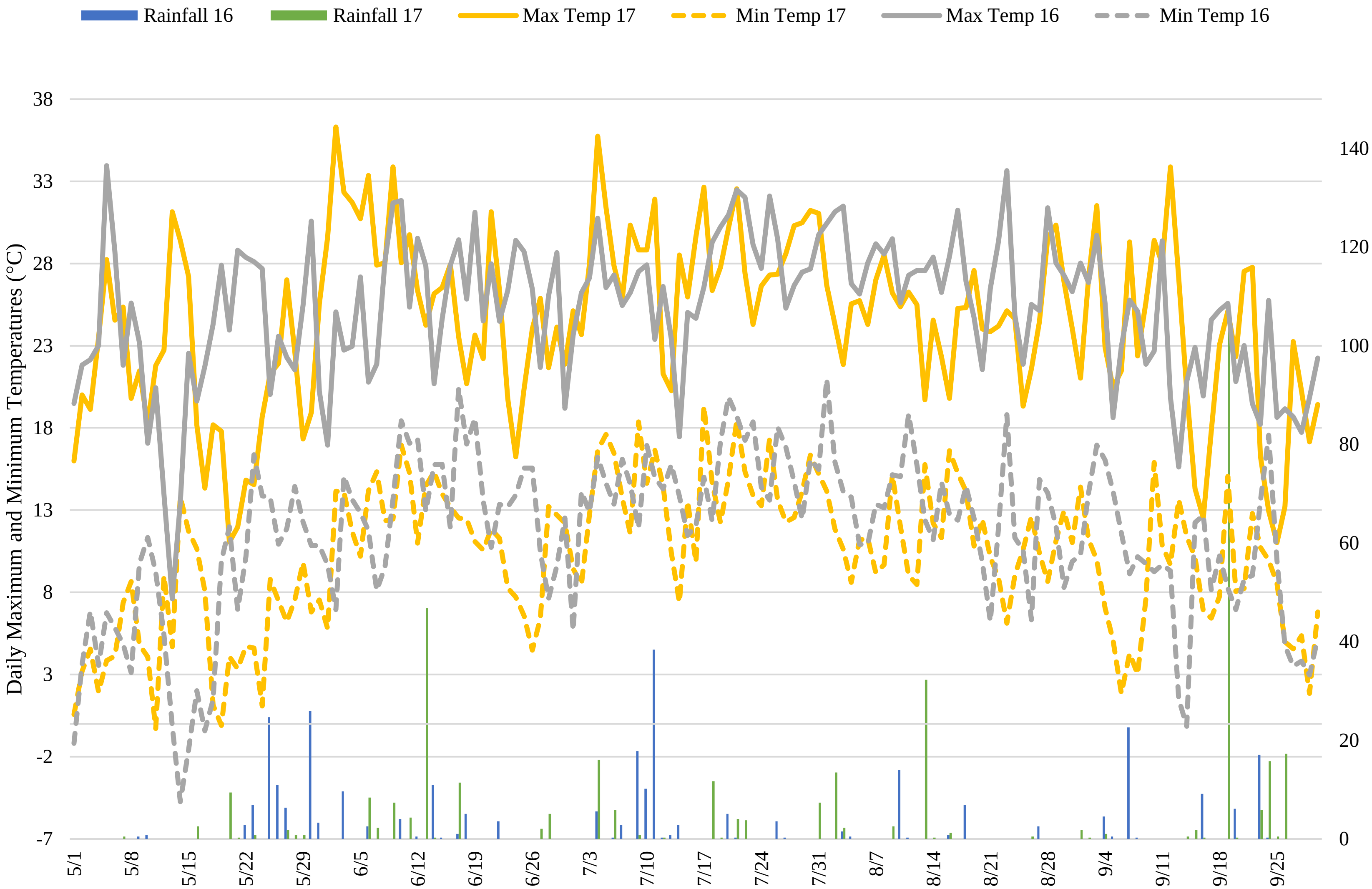

Figure A.3. Daily maximum and minimum air temperatures and daily rainfall totals recorded at Absaraka, ND from May - September 2016 and 2017.

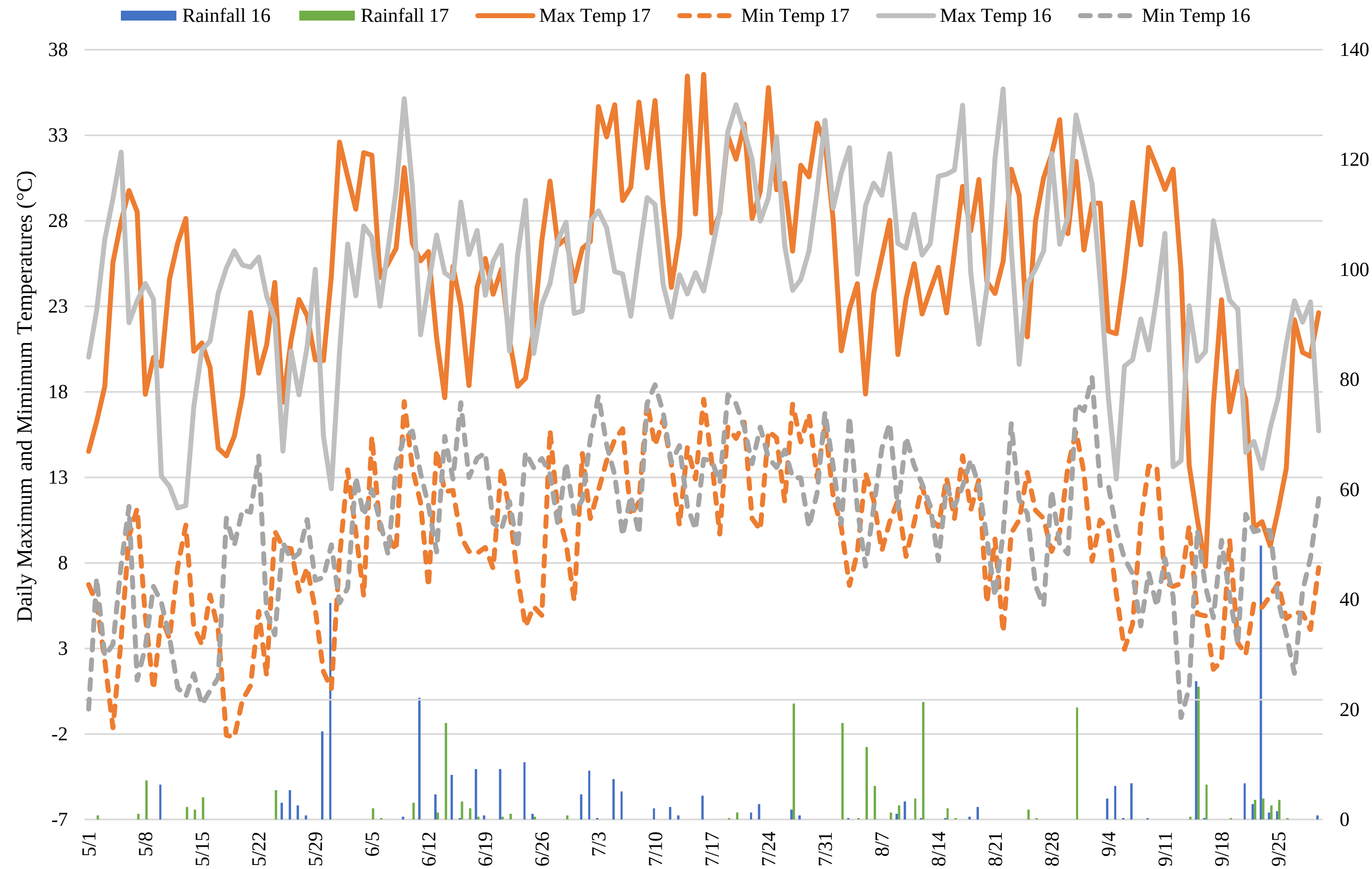

Figure A.4. Daily maximum and minimum air temperatures and daily rainfall totals recorded at Nesson Valley, ND from May - September 2016 and 2017.