MANAGEMENT STRATEGIES FOR THE CULTIVATION OF HOP A SPECIALTY CROP FOR NORTH DAKOTA

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Management Strategies for the Cultivation of Hop a Specialty Crop for North Dakota

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ABSTRACT

Field experiments were conducted in 2017 and 2018 at the NDSU Horticulture Research Farm near Absaraka, ND to evaluate the growth and yield characteristics of twelve commercial hop cultivars in response to varied training densities. Cultivars were trained at two, four, and eight bines per crown each season. Cultivars produced significantly higher yield (kg/ha) trained with eight bines per crown in 2018. ‘Nugget’, and ‘Canadian Red Vine’ significantly yielded highest in 2017. ‘Nugget’, ‘Canadian Red Vine’, and ‘Cascade’ significantly yielded highest in 2018. Research investigating mulching as a weed control method on mature hop production systems was conducted. Hop cultivars ‘Cascade’, ‘Santiam’, and ‘Mt. Hood’ were grown under landscape fabric, straw much, woodchip mulch, and a non-mulched control in a standard hop trellis system. ‘Cascade’ had significantly higher yield, cone size, and biomass compared to cultivars ‘Santiam’ and ‘Mt. Hood’. No significant differences found between mulch treatment selection.

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CHAPTER I. LITERATURE REVIEW

Humulus lupulus L., hop, a herbaceous perennial, is one of four critical ingredients in the production of beer. Post prohibition (1920-1933), total number of beer production facilities within the United States remained relatively low, with less than one-hundred breweries in operation prior to 1980. However, changing consumer preference and pro-alcohol legislation within recent decades have resulted in the establishment of over 7,000 breweries today (Brewers Association, 2018). This increased demand of beer nationwide has subsequently prompted demand in the production of hop. With the high demand for hop products, the opportunity for expanding markets for hop production has opened and prompted increased interest from local growers within North Dakota and other regions not known for their culture. Currently, the majority of the nation's hop production are confined within the Pacific Northwest of the United States. Consequentially, there has been little agronomic research in hop production in non-traditional growing areas.

The following research studies aim to provide accessible information to small scale growers in North Dakota for the successful cultivation of hop. The first study evaluated the success of twelve commercial hop cultivars trained at three different bine densities. Cultivar evaluation is critical in hop production due to the use of different cultivars, which provide varying bittering and aroma components in beer. Many cultivars are blended or are used individually to provide unique styles and tastes to beer, which leads to the demand by brewers for a wide variety of cultivars. Understanding the growth characteristics of particular cultivars in North Dakota will lead to time and labor saved for the growers, and better supply to the local brewing market. Proper fertilization and weed control are critical in the success of all commercial crops. An additional study evaluated four weed control options and three dry nitrogen sources to provide information on options that will best suit growers in North Dakota who plan to grow hop.

Botany

The common hop plant, *Humulus lupulus*, is an herbaceous perennial that produces new shoots from a main crown each spring. These shoots, referred to as bines, climb structures in a clockwise formation with the use of hooked hairs (Figure A2.) along the stem and leaves. *Humulus lupulus,* is a member of the *Cannabaceae* family and is one of three species in the *Humulus* genus, including *H. japonicus,* and *H. yunnanensis.* Although *H. lupulus* is the only species of the genera that is used in brewing. (Neve, 1991). The common hop is a dioecious crop exhibiting separate male and female plants. Since the primary components for brewing from hop are only found in the developed flower cone, or strobilite, the female plant is widely cultivated, only. The hop plant is a vigorous plant that can produce as much as 25 cm of growth per day. The hop plant will grow in a vegetative state until it derives a shortened photoperiodic response that initiates flower formation.

Hop is generally commercially propagated by the separation and cuttings of rhizomes. As particular cultivars are favored for the flavors they impart to the beer, this leads to a demand of sole cultivars being grown in an entire hop yard. The hop plant can stay in farm production well over twenty years, however the production lifespan will depend on the cultivar demand (Turner et al, 2011). The perennial monoculture within a hop yard can cause a number of issues in their production, in relation to insect, disease, weed, and nutrient problems.

Hop plants in commercial production are generally grown on a trellis system that spans 4.5-6.0 meters in the air. This trellis system is made of a framework of poles and suspended cables that allow for training material to be attached. There are various forms of training material from coconut coir, metal wire, or polypropylene line that can be used within a trellis system. These lines are secured at the base of each plant allows for the hop bines to climb up the trellis system.

History

The cultivation of common hop for the use in brewing has taken place for centuries and they were cultivated since the early history the United States. Other major growing regions of hops that have a long and intimate history are areas of Europe such as England, Germany, and the Czech Republic. The initial production of hop in the United States began in the east coast such as New York, and eventually parts of the Midwest such as Wisconsin. Production later moved to the Pacific Northwest (Edwardson, 1952). The move from east to west coast in the United States was due to devastation of the crop caused by disease and insect related issues. As a knowledge of agronomy, horticulture, and general crop production techniques have increased over the last century, producers are now able to better manage the issues that confronted hop production in the late 18th and 19th century. Hop production in non-traditional areas has been revitalized, as the control of the main issues that have historically limited hop production have improved, the demand for craft beer has grown, as has consumer interest in locally grown products. Not only is there renewed interest in non-traditional areas of the United States, but also in other regions of the world, areas such as the Mediterranean. Research in Italy (Rossini et al, 2016) evaluated twenty hop cultivars for potential use in commercial production in the Mediterranean. The study found that their climate had a considerable impact on maturity, flowering date, yield, and quality of each cultivar. More studies evaluating cultivar performance in other regions of the world are critical to better understand how to better grow hop in non-traditional areas.

Brewing Value of Hops

The main hop components of importance in brewing are the alpha acids, beta acids, and essential oils. These components are found in the resin of the lupulin glands of the hop cone. This is golden to yellow resin found in the areas where seeds would be present inside the cone. However, both pollinated and unpollinated cones contain lupulin, but unpollinated cones are generally favored in brewing due contamination issued caused by seeds. Seeded hop cones are considered undesirable by many modern brewers. Alpha acids, with a small contribution by beta acids create the bittering components of beer. The alpha and beta acids are not bitter in their natural state within the cone. The isomerization of the acids into iso-alpha and iso-beta acids during the boiling process of brewing is where bitterness within beer is derived. Essential oils within the lupulin on the other hand are made up of hundreds of volatile compounds that create the aroma in beer. It is the variation in both the bittering and aroma components among different cultivars that make their properties for beer production so varied (Eri et al, 2000). A challenge of hop production is the quick degradation of these important components pre and post-harvest (Taniguchi et al, 2000). If the hop cones are harvested too early in the season, there is low accumulation of these components, however if harvested too late, the components can degrade and cause off flavors. On the other-hand post-harvest processing is also important, adequate drying and reduced exposure to oxygen will allow for the preservation of the desired brewing components. Understanding the timing of maturity of each cultivar is critical for proper harvest timing.

Harvest timing is critical to the color and aroma of products and subsequently their sale and marketability. Research focused variations on pruning and harvest timing on the cultivar ‘Saaz’ at four locations within Slovakia and Czech Republic found that harvest timing had a significant effect on α-acid, linalool, and total oil composition of hop cones. (Matsui et al., 2016). Pruning timing had no effect on hop quality metrics. Additional observations on hop color, suggest that harvest timing plays a factor in final hop color, which can play a major role in the marketability of products.

Additional Uses

Additional uses for hop products have been investigated for their use outside of brewing. Investigation of the used of hop beta acids (HBA) for the control of two-spotted spider mites *Tetranychus urticae* within field hop production has shown promise when paired with other control methods (Jones et al., 2003). Further research has been conducted to investigate the viability of HBA's for the use as a miticide in honey bee colonies against the parasitic mite *Varroa destructor* (DeGrandi-Hoffman et al., 2012). Honey Bee colony heath has been of a serious concern to the science and public communities. 1% treatments of HBA applied to worker bees has shown 86-100% mortality of *Varroa destructor* after 21h of treatment with little effect on the mortality of the bees. HBA's could prove to be an additional tool for bee and honey producers for the overall health and protection of their colonies.

Training Density

Very little recent research has been done on numbers of bines per plant and its relation to yield. Keller and Li (1949) initiated a study evaluating number of bines per plant in relation to yield on the variety 'Fuggle' at Oregon State University in Corvallis, OR. This regression based experiment evaluated number of bines (2, 3, 4, & 5) in its' relationship of cone yield. They found that yield increased in a non-linear fashion as bine density increased. In a further study Keller and Li (1951) evaluated higher densities of bines (4, 5, 6, 7, & 8) in their relationship to yield. They found that densities greater than four showed significantly greater yield but considered six to be the ideal number for bine density. However both of these studies focused on the relationship of yield and bine density on a single cultivar, ‘Fuggle’ and at a research site in the Pacific Northwest. With renewed interest of hop production in the Midwest it is critical to have a better understanding of the effect of bine density on specific cultivar yields.

Alternative Weed Control

Little research has been conducted on the effect of mulching within mature hop yards. Evaluation of mulch types during the establishment of hop, have shown no difference in growth characteristics based on type of mulch (Forward, 2017). Mulching has proven to be an adequate form of weed control in nursery, and high value crop production, in addition to being an alternative to chemical weed control (Skroch et al., 1992)(Lipecki and Berbeć, 1997). In areas where hop production is being introduced, growers have limited access to chemical weed control options as they precede demand for herbicide label registration within the state. Combined with added equipment and material costs, and the increase in herbicide resistant weeds, mulching provides a good alternative for weed control. In addition, mulching can serve as an option for growers wishing to produce hops that meet USDA certified organic status, a sector with growing popularity in the brewing market. However concerns have been made by growers in surrounding regions about mulch types and their impact on total vigor, yield, and hardiness on hop.

Similar research conducted within North Dakota on *Vitis* hybrids investigated the role alternative mulch types play when used in a production setting (Stenger and Hatterman-Valenti, 2016). Their research found that straw, wood chip, and woven polypropylene fabric mulches performed equal control of *Chenopodium album* L. and greater control of *Setaria glauca* L. in comparison to herbicide applications. Additionally these treatments had no effect on the vine establishment within trial. It is unknown if similar results will be achieved in a hop production setting.

Fertilization

Proper fertilization is a critical management strategy to increase yield and quality of many crops. Hops require both adequate water and nutrients throughout the season, particular in the early stages of growth (Lipecki and Berbeć, 1997). Nitrogen in particular is critical growth in all plants. Multi-season applications of nitrogen have shown to increase yields within Solvenian hop yards (Bavec et al., 2003). Nitrogen recommendations for hop production within the United States are of limited scope and non-existent outside of the Pacific North West. Recommendations within the PNW are based around cultivar, yard age, and yield and between 112-168 kg ha^{-1} N annually (Gingrich et al. 2000)(Sullivan et al., 1999). Sullivan also suggests that single fertilizer applications were as effective as split applications in western Oregon trails due to the majority of biomass produced during mid-July to mid-July. The vast differences between North Dakota's environment and the Pacific North West suggest this may not hold true within the state. Multiple applications of fertilizer can add to time and labor costs for small scale growers. A single early season application of nitrogen fertilizer that provides continuous nitrogen would be ideal to growers who have limited labor or no access to fertilizer application through irrigation. It is unknown however if polymer coated urea such as ESN® or urea with urease and nitrification inhibitors such as SuperU® can increase yields through extended nitrogen release.

Objective and Rationale

Little is known about hop growth characteristics within North Dakota and surrounding regions due the majority of United States' hop research centered in the Pacific Northwest. This regional focus has resulted informational gap in hop production in other regions of the country.

Two field experiments were conducted to expand the knowledge of hop growth and culture within North Dakota. Chapter I. details research focused on the evaluation of twelve commercial cultivars and their potential for production within North Dakota. Additionally, this experiment aims to understand the ideal bine density at training, and if differences among cultivars exist. This research will initiate a foundational understanding of which cultivars perform both well or poorly within North Dakota's environment. Scientific data on number of bines trained per plant within modern hop production is lacking. Most anecdotal information suggests 3-4 bines should be trained per line in a traditional hop yard setting. This research aims to better answer that question. A better understanding of the density of bines per plant and the effect on the yield and vigor can greatly impact the productivity of local growers.

Chapter II. describes the effect of various mulching types when combined with alternative nitrogen fertilizer programs. Mulches consisting of wheat straw, mixed wood chip, and woven polypropylene landscape fabric and a non-mulched control weeding were evaluated for their hop growth and yield. In addition, three dry nitrogen sources were evaluated: Urea, SuperU, and Environmentally Smart Nitrogen (ESN) to understand if prolonged nitrogen release would benefit the crop through-out the season. The overall lack of agronomic research in hop both regionally and nationwide present a serious issue for growers. These research components aim to better understand and improve agronomic practices that benefit hop producers of North Dakota and surrounding regions.

CHAPTER II. EASTERN NORTH DAKOTA HOP CULTIVAR EVALUATIONS UNDER VARIED TRAINING DENSITY MANAGEMENT PROGRAMS

Abstract

Expansion of United States hop production beyond the Pacific Northwest, has prompted the need for hop research with a regional focus. North Dakota State University has responded to this demand within the Red River Valley by conducting hop cultivar performance trials and agronomic management trials. In addition, interest in low-input hop yards have prompted an evaluation in hop production with non-supplemental water sources. Field experiments were conducted in 2017 and 2018 at the NDSU Horticulture Research Farm near Absaraka, ND to evaluate the growth and yield characteristics of twelve commercial hop cultivars in response to varied training densities. Cultivars were planted in 2016 on a non-irrigated six meter trellis system with data collection occurring in 2017 and 2018. Bines were trained at two, four ant eight bines per crown. Prior to mechanical harvest; plant biomass, plant height, and harvest bine number were recorded. Post-harvest, cone moisture, cone size, and yield were determined. Cultivars produced significantly higher yield kg ha^{-1} when trained with eight bines per crown in 2018. ‘Nugget’, and ‘Canadian Red Vine’ yielded the highest in 2017, and greater than other cultivars. ‘Nugget’, ‘Canadian Red Vine’, and ‘Cascade’ yielded highest in 2018 and greater than other cultivars. Relatively low yields within the study have prompted interest repeating the trial under irrigated conditions.

Introduction

Within the United States, relatively little is known about the regional growth characteristics, value, and viability of hop production outside the Pacific Northwest. The U.S. craft brewing sector has increased production >20 million barrels since 2014 (340%), which resulted in a substantial increase in the demand for hops in recent years (Brewers Association, 2018). Furthermore, the business model of many new craft brewers has focused on regional ingredients and hop forward beers to initiate and retain consumer interest. This has spurred an increase in the establishment of small scale, non-traditional hop yards across the country. Land grant universities and research institutions have responded to this growth of non-traditional hop yards by conducting hop production research with a regional focus. North Dakota State University has joined this response by conducting research for the eastern portion of the state. This research aims to understand the growth characteristics and performance of a range of hop cultivars. Additionally, this research aims to better understand the relationship between yield and growth factors and bine training densities. These research objectives will establish a foundation for hop production and research within North Dakota's environment.

Material and Methods

Site and Trellis Design

To evaluate cultivar performance under varied training densities, an experimental hop yard was planted in 2016 at the North Dakota State University Horticulture Research and Arboretum site (46° 59'27 N, 97° 21'7 W) near Absaraka, ND. Plot soil profile was a Warsing Sandy Loam, 0-2% slopes (USDA-NCRS, 2019). Following a year of establishment, an experiment and subsequent evaluations were conducted during the 2017 and 2018 growing seasons (May-Oct). Trellis construction consisted of the anchoring of wooden poles (former utility poles) to the height of 5.5 meters. Custom fabricated metal frames were secured to each pole to create a "T" formation. This formation allowed for the attachment of galvanized steel aircraft cable to each side of the metal frames (Figure 2.1.). These parallel cables span the length of the entire row and were anchored to each end pole. Steel anchors were placed in the soil at the base of each plant, allowing for the secure attachment of polypropylene baler twine from anchor to top cables. This process, generally referred to as, "stringing" is conducted on an annual basis at the start of the growing season. Within this research trial, two strings were positioned at each plant crown, creating a "V" formation for hop growth and development. Plants were spaced at 2,415 plant ha^{-1}, 0.9 meters between plants and 4.6 meters between rows. Each row consisted of 36 plants, three plants per cultivar, totaling 144 plants for the research block.


Figure 2.1. North Dakota State University hop trellis system

Treatments

Experimental design was a randomized complete block design with a split plot arrangement, and four replications. The whole plot within the research trail was hop cultivar. Twelve hop cultivars were selected for planting within the research trial in 2016 (Table 2.1.). Cultivar selections were based on availability, historical use, and performance in other non-traditional growing regions. Sub-plots within each whole plot was bine training density. Three training densities were selected as treatments with the study and will be referred to as low, medium, and high. Low training density constituted of one bine trained per line, total of two bines per hop crown. Medium training density; two bines per line, total of four bines per hop crown. High training density; four bines per line, total of eight bines per crown. (Figure 2.2.). Cultivars ‘Fuggle’, ‘Golding’, ‘Northern Brewer’ and ‘Sterling’ were excluded from statistical analysis due to poor establishment within research trail.

Table 2.1. General characteristics of hop cultivars selected for evaluation and planting in 2016

Cultivar	Release Origin	Release Year	Yield (kg ha^{-1})	AA% Range	Brewing Purpose
Canadian Red Vine	Canada	N/A	2240	5.0	Aroma
Cascade	United States	1972	2017-2465	4.5-9.0	Dual
Fuggle	United Kingdom	1875	1008-1233	2.4-6.1	Aroma
Glacier	United States	2000	2400-2600	3.3-9.7	Dual
Golding	United States	N/A	900-1500	4.0-6.0	Aroma
Mt. Hood	United States	1989	1450-1960	4.0-6.5	Aroma
Northern Brewer	United Kingdom	1934	897-1345	7.0-12.1	Bittering
Nugget	United States	1983	2017-2690	9.5-16.0	Dual
Santiam	United States	1997	1430-1780	5.0-8.0	Aroma
Spalter Select	Germany	1993	1750-2000	3.0-6.5	Aroma
Sterling	United States	1998	1800-2000	6.0-9.0	Dual
Willamette	United States	1971	1905-2465	5.2-11.0	Aroma


Figure 2.2. Training density treatments
Left –Right; low, medium, and high training densities on single lines, respectively.

In Season Field Work

Field work involving both research treatments and general crop maintenance were conducted through-out each growing season. Prior to shoot emergence, an application of urea was applied at a rate of 168.12 kg ha^{-1} in 2017 and 224.17 kg ha^{-1} in 2018, respectively. Applications were administered in mid- May with close proximity of hop crowns within treatments. Post shoot emergence, bines were trained to designated treatment numbers beginning at BBCH stage 12. Weekly checks and re-training to proper treatment numbers were conducted until BBCH stage 33. (Rossbauer et al, 1995). Untrained bines remaining in each experimental unit were regularly removed through mechanical pruning, in order to deter stray bines climbing the trellis system and resource competition.

Early Season Phenology

In 2018, early season phenological data was collected to determine if treatments had an effect on emergence and young shoot growth vigor. Visual staging was conducted using BBCH phenology scale for hop (Rossbauer et al, 1995). Visual ratings of hop phenology were conducted on May 11th and May 25th, 2018.

Harvest

Hops were harvested in early to mid-September by cutting bines from the top wire of trellis system and near base of plant crown. Desired harvest was nearest to BBCH growth stage 89, described by full cone closure, bright-golden lupulin, and highest aroma potential. To best fit these descriptions, harvest moisture target was set to 70-80% cone moisture. An early harvest results in poor development of desirable acids and oils for brewing, while a late harvest results in undesirable aromas and loss of volatile compounds within cones. Total number of live bines were recorded per experimental unit, while two samples of bine length were recorded per experimental unit to the nearest tenth of a meter. Total fresh biomass (kg plant^{-1}) was recorded in 2018 only. A fresh harvest index (FHI) was calculated using total fresh yield divided by total fresh biomass in 2018 only. Each experimental unit of bines were passed through the ‘Hopster 5P’ (HopsHarvester LLC. Honeoye Falls, NY) mechanical hop harvester to remove plant biomass from the hop cones. Total harvested fresh yield (kg plant^{-1}) was recorded. Sub-samples of 10 and 50 cones were obtained from each experimental unit with fresh weight recorded to the nearest hundredth. Average cone length and diameter were recorded to the nearest centimeter derived by an average of 10 cones. Sub-samples were placed in a forced-air heated dryer (Chromalox. Pittsburg, PA) at 35°C until field moisture was removed to determine dry weight (g). Fresh and dry weights were used to determine harvest moisture and processed yields

(Equation 2.1.). Processed yield was harvest moisture corrected to 10% moisture content to represent a processed product weight.

$$(Hop\ Dry\ Matter\ \% \div 90) \times Fresh\ Yield = Processed\ Yield \quad \text{(Equation 2.1.)}$$

Statistical Analysis

Data were statistically analyzed through the use of JMP® Pro 14 (SAS Institute Inc. Cary, NC). Phenology, vegetative growth, and yield components were subjected to a linear mixed model. Cultivar and training density were considered fixed effects. Treatment replication was considered a random effect. Mean separation was determined Tukey's honestly significant difference pairwise comparison test at $\alpha \leq 0.05$. Data between years was subjected to separate analysis.

Results and Discussion

Yield Components

Components of yield reported were total fresh yield, harvest moisture, and a derivative of these two values, the processed yield. Within the marketing of hop products, fresh and processed are the two main forms in which hops are sold to the brewing market. Fresh market hop sales are generally focused on the local brewing markets, due to the perishability of a non-processed product. In growing regions with limited and small scale production, fresh market hops provide differentiation with the increasingly competitive hop markets, and lower capital investments in harvest and processing infrastructure. Significant cultivar differences in fresh yield (kg ha^{-1}) were observed in both 2017 and 2018 (Table 2.2.). In 2017, all cultivars with the exception of ‘Spalter Select’ produced >1,500 kg ha^{-1} Fresh Yield. ‘Nugget’ produced greatest yield, significantly greater than ‘Mt. Hood’, ‘Santiam’, and ‘Spalter Select’. Training density treatments were significant $\alpha \leq 0.10$ but not $\alpha \leq 0.05$ in 2017. High and medium density treatments produced significantly greater yields than the low density training treatment. Fresh yield differences between cultivars in mean separation became more distinct in 2018, where ‘Canadian Red Vine’, ‘Cascade’, and ‘Nugget’ were significantly higher than all other cultivars evaluated within the trial. Training density treatments were significant at $\alpha \leq 0.05$ in 2018. High density training produced significantly greater yields than low and medium training densities. No interactions between cultivar and training density were found.

Although important in determination from a fresh market business model, fresh yields can be skewed greatly, due to cone moisture at harvest with variations between cultivars within a single season or harvest timing from one year to another. Harvest yields corrected to reflect cones bound for a processed product end use (T-90 pellets, whole cone, CO_2 extract, etc.) more accurately reflect cultivar and treatment performance. Similarly ‘Canadian Red Vine’ and ‘Nugget’ exhibited greatest processed yields in 2017, followed by ‘Cascade’ (Table 2.2.). ‘Santiam’ and ‘Spalter Select’ had the lowest processed yields, significantly less than ‘Canadian Red Vine’, ‘Nugget’, and ‘Cascade’. In regard to training density treatments in 2017, significant differences were only observed at $\alpha \leq 0.10$, with medium and high density treatments yielding significantly greater than low training densities. In 2018, processed yield trends mirrored fresh yield data, with ‘Canadian Red Vine’, ‘Nugget’, and ‘Cascade’ yielding significantly greater than all other cultivars. High training densities yielded significantly greater than low, and medium trained densities at $\alpha \leq 0.05$. It is important to note that decreases in processed yield in 2018 in comparison to 2017 yields were observed across all cultivars and treatments. This was attributed due to the differences in harvest moisture range between the two years (Table 2.2.). In 2017, harvest moisture ranged between 57.1- 66.7% in comparison to 72.4- 76.0% in 2018.

These differences lead to misleading results between the two years in regards to fresh yield performance.

Harvest moisture is one method used to help determine plant maturity and cone harvest readiness. In many newer growing regions this is the primary method used, as other forms are primarily anecdotal, and experiential. Additionally, harvest moisture is needed to determine accurate drying timing. Ideal moisture for stored and processed products are between 8-12%. Over-drying of cones will lead to shattering and loss in volatile oils, while under-drying will lead to decomposition and mold development. Training treatments or interactions between training and cultivars had no significant effect on harvest moisture in both years (Table 2.2.). Harvest moisture was also similar for all cultivars with the exception of 'Spalter Select' in 2017, indicating that 'Spalter Select' matured earlier than other cultivars evaluated in the trail. In 2018, harvest moisture of 'Mt. Hood' was significantly greater than 'Glacier', 'Santiam', and 'Spalter Select', indicating that 'Mt. Hood' potentially matures later than these respective cultivars. Understanding maturation timelines within distinct growing regions can assist growers in determining harvest dates within their specific hop yard setups.

Table 2.2. Fresh yield, processed yield, and harvest moisture for hops grown at NDSU Horticultural Research Farm, Absaraka, ND in 2017 and 2018.

	Fresh Yield (kg ha^{-1})		Processed Yield (kg ha^{-1})		Harvest Moisture (%)	
	2017	2018	2017	2018	2017	2018
Cultivar (C)						
Canadian Red Vine	4237 ab[z]	4788 a	1738 a	1304 a	63.5 a	75.4 ab
Cascade	3859 abc	5099 a	1560 ab	1504 a	64.5 a	73.4 abc
Glacier	2207 abcd	1406 b	958 abc	413 b	60.3 ab	72.4 bc
Mt. Hood	2065 bcd	1241 b	752 bc	335 b	66.7 a	76.0 a
Nugget	4248 a	4421 a	1627 a	1316 a	66.0 a	72.7 bc
Santiam	1611 cd	989 b	655 c	277 b	64.8 a	74.6 abc
Spalter Select	568 d	878 b	264 c	271 b	57.1 b	72.4 c
Willamette	2576 abcd	2229 b	1209 abc	661 b	65.0 a	73.2 abc
Density (D)						
Low	2039 b	924 b	818 b	645 b	63.7 [ns]	73.4
Medium	2961 a	980 b	1233 a	681 b	63.4	73.8
High	3013 a	1364 a	1236 a	953 a	63.7	74.0
Source						
C	<.0001 **	<.0001 **	<.0001 **	<.0001 **	<.0001 **	0.0010 **
D	0.0878 +	0.0038 **	0.0509 +	0.0025 **	0.9523	0.6355
C x D	0.7844	0.1769	0.6898	0.2173	0.2667	0.4978

[z] Different letters following means within main effects represent significant differences according to Tukey's HSD (α≤ 0.05)

+,*, ** significant main effects and interactions at P≤ 0.10, 0.05, and 0.01, respectively.

[ns] main effect not significant at P≤ 0.05

Cone Dimensions

As hop cones are the primary and desired botanical aspect of *Hulmulus lupulus*, average cone length and widths of sample were measured and recorded for statistical analysis. Significant differences between cultivars in both years $\alpha \leq 0.05$ were observed for both cone width and length (Table 2.2.). No significant differences were observed between training densities or interactions between main effect for cone width and length in either year. An overall decrease of cone width and lengths was observed from 2017 to the 2018 growing season. Differences between cultivars within trial are considered to be primarily differences in genotype cone morphology and performance within trial.

Table 2.3. Cone width and lengths for hops grown at NDSU Horticultural Research Farm, Absaraka, ND in 2017 and 2018.

	Cone Width (cm)		Cone Length (cm)	
	2017	2018	2017	2018
Cultivar (C)				
Canadian Red Vine	17.0 ab[z]	15.0 a	23.2 Bc	20.6 bc
Cascade	15.6 bcd	13.1 abc	27.9 A	30.1 a
Glacier	13.8 d	10.5 c	15.4 D	12.7 d
Mt. Hood	16.8 abc	12.5 abc	24.0 abc	16.8 cd
Nugget	17.7 a	14.9 a	27.5 Ab	23.0 b
Santiam	18.6 a	13.9 ab	24.7 abc	19.9 bc
Spalter Select	14.9 cd	11.9 bc	22.7 C	16.3 cd
Willamette	17.2 ab	14.2 ab	22.4 C	18.0 c
Density (D)				
Low	16.7 [ns]	13.0	23.2	19.5
Medium	16.7	13.3	24.1	19.4
High	16.0	13.4	23.1	20.4
Source				
C	<.0001 **	<.0001 **	<.0001 **	<.0001 **
D	0.1898	0.7842	0.5011	0.5093
C x D	0.8488	0.3272	0.9260	0.2299

[z] Different letters following means within main effects represent significant differences according to Tukey's HSD ($\alpha \leq$ 0.05)
*, ** significant main effects and interactions at $P \leq 0.05$ and 0.01, respectively.
[ns] main effect not significant at $P \leq 0.05$

Early Season Phenology

Visual ratings using the BBCH hop phenology scale (Rossbauer et al, 1995) were taken during two separate periods in May, 2018. The purpose of these ratings were to determine if the previous year's treatments affected the overall emergence and overall initial growth of the hop and differences amongst cultivars. Two phenology ratings were conducted in May, on the 11th and the 25th (Table 2.4.) Phenology between cultivars was significantly different during both rating periods. On May 5th, 'Nugget' and 'Santiam' were the most advanced in growth stages and were significantly greater than 'Canadian Red Vine' and 'Willamette'. During the May 25th rating, 'Cascade' and 'Mt. Hood' were significantly more advanced in growth stage than 'Canadian Red Vine'. These differences between cultivar in early season growth seem to have no effect on eventual outcome of yield and growth characteristics. Significant differences between growth stage and training density were observed on the May, 11th rating, but not on May 25th. Differences in phenology between training density were observed on May 11th, however cannot be explained.

Table 2.4. Early season plant phenology for hops grown at NDSU Horticultural Research Farm, Absaraka, ND in 2017 and 2018.

	BBCH	
	05/11/18	05/25/18
Cultivar (C)		
Canadian Red Vine	12.9 bc[z]	14.9 b
Cascade	13.5 ab	16.0 a
Glacier	13.2 abc	15.2 ab
Mt. Hood	13.6 ab	16.2 a
Nugget	13.7 a	15.8 ab
Santiam	13.7 a	15.4 ab
Spalter Select	13.0 abc	15.5 ab
Willamette	12.6 c	15.4 ab
Density (D)		
Low	13.1 b	15.4 [ns]
Medium	13.3 ab	15.6
High	13.5 a	15.4
Source		
C	<.0001 **	0.0100 **
D	0.0396 *	0.2734
C x D	0.1516	0.8811

[z] Different letters following means within main effects represent significant differences according to Tukey's HSD ($\alpha \leq 0.05$)
*, ** significant main effects and interactions at $P \leq 0.05$ and 0.01, respectively.
[ns] main effect not significant at $P \leq 0.05$

Bine Height and Surviving Bines

Other growth characteristics were determined at harvest to gauge overall plant vigor and plant responses to treatments and environments. Total height of bines, total number of harvested bines, fresh biomass, and fresh harvest index were recorded at harvest. Fresh biomass and fresh harvest index were recorded in 2018 only. Significant differences between cultivars were observed between total bine height in 2017 and 2018 (Table 2.5.). Training density had no significant effect on total bine height during either year. ‘Glacier’ and ‘Willamette’ had significantly greater heights recorded in 2017 than ‘Spalter Select’. Conversely, ‘Nugget’ and ‘Mt. Hood’ were significantly greater in bine height than ‘Santiam’ and ‘Spalter Select’.

Total number of surviving bines at harvest were recorded in 2017 and 2018. These values are critical in understanding the response of cultivars to training and if training treatments actually resulted in differences in total bine number at harvest. No significant differences were observed between cultivar in 2017 for total bines harvest, indicating that all cultivars responded similarly to training treatments during the first year of the trial (Table 2.5.). However significant differences in total harvested bines between cultivar was observed in 2018. ‘Nugget’ had significantly greater average of harvested bines in comparison to ‘Spalter Select’. ‘Spalter Select’ likely exhibited poorer trainability due to the low vigor of the cultivar within the trial. Mean separations of total harvested bines were observed between all training treatments during both years. As expected, higher training treatments resulted in significantly greater number of bines harvested. Interestingly, deviations of number of harvested bines increased as training density increased. Deviations from the trained bine number can occur throughout the season due field losses such as disease and insect pressure as well as in increases due to rouge bines climbing mid-season.

Table 2.5. Bine height and total bines harvested for hops grown at NDSU Horticultural Research Farm, Absaraka, ND in 2017 and 2018.

	Bine Length (m)		Total Bines Harvested (Bine plant^{-1})	
	2017	2018	2017	2018
Cultivar (C)				
Canadian Red Vine	4.42 ab[z]	5.22 ab	3.30 [ns]	3.83 ab
Cascade	4.31 ab	5.14 ab	4.0	4.44 ab
Glacier	5.18 a	5.03 ab	3.13	3.41 ab
Mt. Hood	4.74 ab	5.97 a	3.08	3.83 ab
Nugget	4.81 ab	5.96 a	3.91	4.58 a
Santiam	4.64 ab	4.54 b	3.03	3.74 ab
Spalter Select	3.26 b	4.88 b	2.64	3.25 b
Willamette	4.89 a	5.40 ab	3.5	3.91 ab
Density (D)				
Low	4.26	5.17	2.1 C	2.0 c
Medium	4.49	5.30	3.2 B	3.7 b
High	4.85	5.33	4.6 A	6.0 a
Source				
C	0.0300 *	<.0001 **	0.2045	0.0384 *
D	0.2002	0.6787	<.0001 **	<.0001 **
C x D	0.7218	0.0915	0.2279	0.0438 *

[z] Different letters following means within main effects represent significant differences according to Tukey's HSD ($\alpha \leq 0.05$)
*,** significant main effects and interactions at $P \leq 0.05$ and 0.01, respectively.
[ns] main effect not significant at $P \leq 0.05$

Biomass and Fresh Harvest Index

Total fresh biomass (kg plant^{-1}) recorded in 2018, was significant between cultivar and training density main effects at $\alpha \leq 0.05$ (Table 2.6.). 'Canadian Red Vine' and 'Nugget' produced the greatest amount of biomass with means greater than 5.9 kg plant^{-1}, these cultivars produced significantly more biomass than 'Glacier', 'Mt. Hood', 'Santiam', 'Spalter Select' and 'Willamette'. High training densities produced significantly higher amounts of fresh biomass when compared to low and medium density training treatments. Higher amounts of total biomass were expected due to increased number of bines trained during the vegetative growth stages. Surprisingly, no differences were observed between the low and medium treatments, but reflects similar trends in yield components (Table 2.2.).

A fresh harvest index (FHI) was calculated to observe the relationship between total biomass and total fresh yield of hop treatments. Ideally this index would have been created from values corrected for moisture content, however this value was unobtainable due to the total size and complexity of determining accurate dry mass values. A higher harvest index represents a higher ratio of yield component to total plant mass. Fresh harvest index was significantly different between cultivars (Table 2.6.). 'Cascade' had a significantly greater FHI than all other cultivars within trial, 'Mt. Hood' and 'Santiam' had the lowest FHI observed. FHI ratios seem to associate with anecdotal field observations on ease of harvest across cultivar, most likely accounting to the higher proportion of yield components in comparison to other vegetative mass. No significant differences were observed between FHI of training density treatments.

Conclusions

The establishment of baseline and foundational data for successful and viable hop production within North Dakota were the initial drivers of this study. The primary objective of this research was to identify cultivars that produced well in North Dakota's environment on an annual basis. In addition to identifying productive cultivars, this research aimed to identify the ideal training densities for the region and if the optimum number of bines varied between cultivars. The greatest yielding cultivars within the research trial were 'Canadian Red Vine', 'Cascade', and 'Nugget' in 2017 and 2018, and should be considered as candidates for commercial production in North Dakota. However, it should be noted that marketability of final hop products should be taken in consideration when selecting cultivars for production. In general, hop products are sold as individual cultivars and demand varies vastly from one cultivar to another. 'Canadian Red Vine' is one such cultivar in which sees high potential for yield but its marketability is low to non-existent in some regions. Training at a high density of bine plant^{-1} proved to be the most beneficial for both fresh and processed yield. As expected there was variation in harvest moisture between cultivars due to varied maturation times, but only in 2018. The advanced field moisture loss in 2017 is a likely explanation why no differences between cultivar were observed. Increasing training density had no deleterious effect on harvest moisture, cone dimensions, phenology, bine length, or fresh harvest index throughout the study. Additionally, it is unknown if increasing trained bine number above the 'High density' treatment within this study will further benefit hop yields or if a plateau in bine number and subsequent yields can be reached.

A decrease in yield was observed all cultivars and training treatments from 2017 to 2018. Subsequent years of low rainfall or inadequate annual fertilization as the crop has matured could be a key factors in why reduced yields were observed. The sheer lack of agronomic research of hop within the state and surrounding regions have prompted a vast information gap for new growers. Further investigation into the evaluation of additional cultivars, supplementary water, and nutrient management are key areas for future research in North Dakota hop production.

Table 2.6. Fresh biomass and fresh harvest index for hops grown at NDSU Horticultural Research Farm, Absaraka, ND in 2017 and 2018.

	Biomass (kg plant^{-1})	Fresh Harvest Index
	2018	2018
Cultivar (C)		
Canadian Red Vine	6.96 a[z]	0.28 bc
Cascade	5.56 ab	0.38 a
Glacier	2.29 cd	0.23 cde
Mt. Hood	2.93 cd	0.18 e
Nugget	5.93 a	0.31 b
Santiam	2.11 cd	0.18 e
Spalter Select	1.81 d	0.20 de
Willamette	3.74 bc	0.25 bcd
Density (D)		
Low	3.02 b	0.26 [ns]
Medium	3.64 b	0.24
High	5.08 a	0.25
Source		
C	<.0001 **	<.0001 **
D	<.0001 **	0.2744
C x D	0.2299	0.3796

[z] Different letters following means within main effects represent significant differences according to Tukey's HSD ($\alpha \leq 0.05$)

*, ** significant main effects and interactions at $P \leq 0.05$ and 0.01, respectively.

[ns] main effect not significant at $P \leq 0.05$

Table 2.7. Rainfall recorded at NDAWN station Prosper, ND 2016-2018

	Rainfall (cm)		
	2016	2017	2018
April	4.31	1.65	0.38
May	8.21	1.68	5.39
June	3.76	8.79	7.93
July	8.79	5.00	6.53
August	2.64	5.26	7.85
September	6.05	15.17	7.09
October	4.86	0.69	6.66
Total	38.62	38.24	41.83

Table 2.8. Accumulated Growing Degree Days May 1st- September 30th, 2017 & 2018 NDAWN Prosper

	GDD	
	2017	2018
May	168	256
June	275	313
July	340	319
August	258	295
September	192	177
Total	1233	1360

CHAPTER III. EVALUATION OF MULCH WEED CONTROL OPTIONS WITHIN VARIED NITROGEN PROGRAMS IN MATURE HOP YARDS

Abstract

Hop (Humulus lupulus L.) a herbaceous perennial, is a high value crop critical in beer production. Interest to grow hop as niche local market crop have become increasingly popular in areas not known for the crop's culture, such as North Dakota. Little research on hop growth and production techniques in the United States have been conducted outside the Pacific Northwest. Consequently, non-traditional growing areas generally have few chemical options registered for use in hop production. Furthermore, increases in herbicide resistance species, food product regulation constrains, and diversification of production systems have prompted interest in herbicide alternative weed control methods. This research aims to evaluate the effect of mulching use as an alternative weed control method on mature hop production systems. Field experiments were conducted in 2017 & 2018 at the NDSU Horticulture Research site near Absaraka, ND to evaluate the growth and yield characteristics of three commercial hop cultivars in response to mulch weed control options and nitrogen fertilizer sources. Hop cultivars 'Cascade', 'Santiam', and 'Mt. Hood' were grown under landscape fabric, straw much, woodchip mulch, and a non-mulched control in a standard hop trellis system. Nitrogen sources used were Urea, SuperU and ESN. Plant biomass, plant height, cone dimensions, and yield were taken prior and after mechanical harvest. 'Cascade' had significantly higher yield, cone size, and biomass compared to cultivars 'Santiam' and 'Mt. Hood'. However, no significant differences were found between mulch or nitrogen treatment selections. Results suggest potential for a variety of mulching options to be used by growers and hop as a specialty crop in North Dakota.

Introduction

With no historical and very limited modern hop production within North Dakota, interested growers have relatively little information on regional agronomic practices for their systems. Additionally, many of the hop yards outside the traditional U.S. growing region are small scale and vary considerably in trellis systems, in-season management, and cultivar selection. Two of the many challenges for non-traditional growers face are options for weed control and information on nutrient needs and fertilization. Relatively few chemistries for weed control are available for use on hop in North Dakota and surrounding states. While there are non-chemical options for weed control available for growers, there is no data available to growers to address the viability and outcomes of their use. Mulching as a form of weed control has proven to be a successful option in many perennial cropping systems. Research during the establishment of hop has shown that mulching is an effect form of weed control in comparison to a non-mulched control (Forward, 2017) However, the effect of mulch systems on a multi-year basis within mature hop yards is unknown. There is concerns that mulch may reduce the overall hardiness and vigor of hop due to the rhizomatous nature of the plant (Figure A3.). Due to the vigor and biomass produced on an annual basis by hop, proper nitrogen fertilization of hop is of serious interest of growers within the region. Use of dry nitrogen fertilizer sources are of interest due to the accessibility, and ease of application for small scale growers. Forward 2017, found that nitrogen source choice had no effect on growth characteristics during the establishment of hop. It is unknown if this holds true in mature hop production systems that have higher annual nutrient requirements. The project objective was to provide information on mulch and nitrogen choices and their use in a mature hop yard in North Dakota.

Material and Methods

Site and Trellis Design

To evaluate cultivar performance under various mulch types and nitrogen sources, two sections of an experimental hop yard were planted in 2015 and 2016 at North Dakota State University Horticulture Research and Arboretum site (46° 59’27 N, 97° 21’7 W) near Absaraka, ND. Plot soil profile was a Warsing Sandy Loam, 0-2% slopes (USDA-NCRS, 2019). Following two years of establishment, an experiment and subsequent evaluations were conducted during the 2017 and 2018 growing seasons (May-Oct). Trellis construction consisted of the anchoring of wooden poles (former utility poles) to the height of 5.5 meters. Custom fabricated metal frames were secured to each pole to create a “T” formation. This formation allowed for the attachment of galvanized steel aircraft cable to each side of the metal frames (Figure 2.1.). These parallel cables span the length of the entire row and were anchored to each end pole. Steel anchors were placed in the soil at the base of each plant, allowing for the secure attachment of polypropylene baler twine from anchor to top cables. This process, generally referred to as, “stringing” was conducted on an annual basis at the start of the growing season. Within this research trial, two strings were positioned at each plant crown, creating a “V” formation for hop growth and development. Plants were spaced at 2,415 plant ha^{-1}, 0.9 meters between plants and 4.6 meters between rows. Each row consisted of 36 plants, 12 plants per cultivar, totaling 144 plants for each research block. A total of 288 experimental units were evaluated within this research trial.

Treatments

Experimental design was a randomized complete block design with a split-split plot arrangement, and four replications. The whole plot within the research trail was hop cultivar. Three hop cultivars were selected for planting within the research trial in 2015 and 2016 (Table

2.1). Cultivar selections were based on availability, historical use, and performance in other non-traditional growing regions. Sub-plots within each whole plot was mulching type. Three mulch types and a non-treated control were selected as treatments within the study. Woven black polypropylene commonly known as landscape fabric, wheat straw, and mixed woodchips were selected as mulch sources used in this trial based on their differences in cost, availability, and labor requirements (Figure 3.1.). Mulch treatments encompassed a 0.9 x 0.9 meter area for each experimental unit. Mulch treatments were established and maintained since planting in 2015 & 2016, respectively. Sub-sub plot within the research trail was bine nitrogen source. Nitrogen sources used as treatments included a single early season application of urea, SuperU®, or ESN® polymer coated urea at a rate of 224.17 kg ha^{-1} annually. Prior to shoot emergence, nitrogen treatments were integrated within or under mulch treatments in close proximity of hop crowns.

Table 3.1. General characteristics of hop cultivars selected for evaluation and planting in 2015 and 2016.

Cultivar	Release Origin	Release Year	Yield (kg ha^{-1})	AA% Range	Brewing Purpose
Cascade	United States	1972	2017-2465	4.5-9.0	Dual
Mt. Hood	United States	1989	1450-1960	4.0-6.5	Aroma
Santiam	United States	1997	1430-1780	5.0-8.0	Aroma


Figure 3.1. Mulching treatments
Left –Right; mixed woodchip, landscape fabric, wheat straw, non-mulched control, respectively. Images taken prior of second season re-application of mixed woodchip and wheat straw mulch.

In Season Field Work

Field work involving both research treatments and general crop maintenance were conducted through-out each growing season. Post shoot emergence a total of four bines per plant were trained, resulting in two per line on the trellis system. Training commenced at BBCH stage 12. Weekly checks and re-training to proper treatment numbers were conducted until BBCH stage 33 (Rossbauer et al, 1995). Untrained bines remaining in each experimental unit were regularly removed through mechanical pruning, in order to deter stray bines climbing the trellis system and resource competition.

Early Season Phenology

In 2018, early season phenological data was collected to determine if treatments had an effect on emergence and young shoot growth vigor. Visual staging was conducted using BBCH phenology scale for hop (Rossbauer et al, 1995). Visual ratings of hop phenology were conducted on May 11th and May 18th, 2018.

Harvest

Hops were harvested in early to mid-September by cutting bines from the top wire of trellis system and near the base of plant crown. Desired harvest was nearest to BBCH growth stage 89, described by full cone closure, bright-golden lupulin, and highest aroma potential. To best fit these descriptions, harvest moisture target was set to 70-80% cone moisture. An early harvest results in poor development of desirable acids and oils for brewing, while a late harvest results in undesirable aromas and loss of volatile compounds within cones. Total number of live bines were recorded per experimental unit, while two samples of bine length were recorded per experimental unit to the nearest tenth of a meter. Total fresh biomass (kg plant^{-1}) was recorded in 2018 only. A fresh harvest index (FHI) was calculated using total fresh yield divided by total fresh biomass in 2018 only. Each experimental unit of bines were passed through the 'Hopster 5P' (HopsHarvester LLC. Honeoye Falls, NY) mechanical hop harvester to remove plant biomass from the hop cones. Total harvested fresh yield (kg plant^{-1}) was recorded. Sub-samples of 10 and 50 cones were obtained from each experimental unit with fresh weight recorded to the nearest hundredth. Average cone length and diameter were recorded to the nearest centimeter derived by an average of 10 cones. Sub-samples were placed in a forced-air heated dryer (Chromalox. Pittsburg, PA) at 35°C until field moisture was removed to determine dry weight (g). Fresh and dry weights were used to determine harvest moisture and processed yields (Equation 2.1). Processed yield was harvest moisture corrected to 10% moisture content to represent a processed product weight.

Statistical Analysis

Data were statistically analyzed through the use of JMP® Pro 14 (SAS Institute Inc. Cary, NC). Phenology, vegetative growth, and yield components were subjected to a linear mixed model. Cultivar, mulching, and nitrogen treatments were considered fixed effects. Planting block and treatment replication were treated as random effects. Mean separation was determined using Tukey's Honestly Significant Difference pairwise comparison test at $\alpha \leq 0.05$. Data between years was subjected to separate analysis.

Results and Discussion

Yield Components

Components of yield reported were total fresh yield, harvest moisture, and a derivative of these two values, the processed yield. Within the marketing of hop products, fresh and processed are the two main forms in which hops are sold to the brewing market. Fresh market hop sales are generally focused to the local brewing markets, due to the perishability of a non-processed product. In growing regions with limited and small scale production, fresh market hops provide differentiation with the increasingly competitive hop markets, and lower capital investments in harvest and processing infrastructure. Statistical analysis of fresh yields found no significant differences between observations in 2017 and 2018 for both mulch, and nitrogen main effects or interactions between treatments (Table 3.2.) Fresh yields between cultivars were significantly different in 2017 and 2018. 'Cascade' yielded significantly greater than both 'Mt. Hood' and 'Santiam' in 2017 and 2018. Yield decreases were observed from 2017 to 2018 across all cultivars.

Although important in determination from a fresh market business model, fresh yields can be skewed greatly due to cone moisture at harvest with variations between cultivars within a single season or harvest timing from one year to another. Harvest yields corrected to reflect cones bound for a processed product end use (T-90 pellets, whole cone, CO_2 extract, etc.) more accurately reflect cultivar and treatment performance. Mulch and nitrogen treatments or interactions between treatments did not significantly processed yields in 2017 and 2018 (Table 3.2.). Processed yield between cultivars were significantly different in 2017 and 2018. Again ‘Cascade’ was significantly greater in processed yield in comparison to ‘Mt. Hood’ and ‘Santiam’ for both years. Processed yield decreases were also observed from 2017 to 2018 across all cultivars.

Harvest moisture is one method used to help determine plant maturity and cone harvest readiness. In many newer growing regions this is the primary method, as other forms are primarily anecdotal, and experiential. Additionally, harvest moisture is needed to determine accurate drying timing. Ideal moisture for stored and processed products are between 8-12%. Over-drying of cones will lead to shattering and loss in volatile oils, under-drying will lead to decomposition and mold development. There were no significant differences in harvest moisture between all treatments, interactions, and cultivars in both 2017 and 2018 (Table 3.2.).

Table 3.2. Fresh yield, processed yield, and harvest moisture for hops grown at NDSU Horticultural Research Farm, Absaraka, ND in 2017 and 2018

	Fresh Yield (kg ha^{-1})		Processed Yield (kg ha^{-1})		Harvest Moisture (%)	
	2017	2018	2017	2018	2017	2018
Cultivar (C)						
Cascade	3523 a[z]	2978 a	1140 a	1031 a	64.1	68.6
Mt. Hood	1963 b	949 b	535 b	302 b	69.4	70.75
Santiam	1521 b	724 b	444 b	230 b	67.0	71.0
Mulch (M)						
Landscape Fabric	2535[ns]	1728	746	570	67.8	70.7
Wood Chip	2163	1487	670	508	64.9	68.7
Wheat Straw	2234	1446	671	488	67.1	70.3
Control	2412	1542	738	516	67.6	70.7
Nitrogen (N)						
Urea	2282	1508	662	504	67.9	70.6
SuperU	2408	1547	762	519	64.5	70.5
ESN	2318	1596.5	694	539	68.0	69.3
Source						
C	<.0001 **	<.0001 **	<.0001 **	<.0001 **	0.2011	0.1584
M	0.5361	0.1812	0.8641	0.3499	0.8309	0.5265
N	0.8670	0.7631	0.5891	0.6917	0.3983	0.5626
C x M	0.3893	0.9464	0.9989	0.9190	0.4209	0.2927
C x N	0.5410	0.6569	0.4866	0.6145	0.4152	0.4690
M x N	0.8316	0.6780	0.7567	0.6513	0.4641	0.4004
C x M x N	0.7831	0.4109	0.8605	0.7398	0.4848	0.2682

[z] Different letters following means within main effects represent significant differences according to Tukey's HSD ($\alpha \leq 0.05$)

*, ** significant main effects and interactions at $P \leq 0.05$ and 0.01, respectively.

[ns] main effect not significant at $P \leq 0.05$

Cone Dimensions

As hop cones are the primary and desired botanical aspect of *Hulmulus lupulus*, average cone length and widths of sample were measured and recorded for statistical analysis. Significant differences between cultivars in both years $\alpha \leq 0.05$ were observed for both cone width and length. No significant differences were observed between mulch and nitrogen treatments or interactions between treatments for cone width and length in 2017 and 2018; excluding cone length by mulching treatment in 2018 (Table 3.3.). 'Santiam' had significantly higher average cone width over 'Mt. Hood' and 'Cascade' in 2017 and 2018. 'Cascade' had significantly higher average cone length over 'Santiam' and 'Mt. Hood' in 2017 and 2018. Differences between cultivars within trial are considered to be primarily differences in genotype cone morphology and not necessarily a representation of overall cultivar performance. Cone lengths were significantly greater in 2018 under landscape mulching in comparison to the wheat straw mulch.

Table 3.3. Cone width and lengths for hops grown at NDSU Horticultural Research Farm, Absaraka, ND in 2017 and 2018.

	10 Cone Width (cm)		10 Cone Length (cm)	
	2017	2018	2017	2018
Cultivar (C)				
Cascade	15.2 c[z]	11.6 c	25.6 a	20.7 a
Mt. Hood	16.9 b	12.3 b	22.0 b	15.8 c
Santiam	18.4 a	13.7 a	22.7 b	17.5 b
Mulch (M)				
Landscape Fabric	17.1 [ns]	12.7	23.9	18.9 a
Wood Chip	16.9	12.8	23.8	17.5 ab
Wheat Straw	16.8	12.2	23.0	17.4 b
Control	16.6	12.5	23.9	18.2 ab
Nitrogen (N)				
Urea	16.6	12.6	22.7	18.2
SuperU	16.9	12.5	23.6	18.1
ESN	16.9	12.6	23.9	17.7
Source				
C	<.0001 **	<.0001 **	<.0001 **	<.0001 **
M	0.3700	0.2052	0.2572	0.0260 *
N	0.4115	0.6563	0.1048	0.4732
C x M	0.7413	0.9022	0.4263	0.1136
C x N	0.3971	0.5896	0.5663	0.5605
M x N	0.9504	0.6558	0.6238	0.4170
C x M x N	0.9989	0.8212	0.9961	0.8508

[z] Different letters following means within main effects represent significant differences according to Tukey's HSD ($\alpha \leq 0.05$)
*, ** significant main effects and interactions at $P \leq 0.05$ and 0.01, respectively.
[ns] main effect not significant at $P \leq 0.05$

Early Season Phenology

Visual ratings using the BBCH hop phenology scale (Rossbauer et al, 1995) were taken during two separate periods in May, 2018. The purpose of these ratings were to determine if the previous year's treatments affected the overall emergence and overall initial growth of the hop and differences amongst cultivars. Two phenology ratings were conducted in May, on the 11th and the 18th. No significant differences were observed for cultivar and nitrogen source main effects during both rating periods (Table 3.4.) Significant differences between mulch selections were observed during both rating periods. Bine growth stages were more advanced for the un-mulched control during both ratings May 11th and 18th in comparison to wheat straw and wood chip mulch types. Bines under the landscape fabric mulching were more advanced than the wheat straw and wood chip mulch types on the May 11th ratings. The delay in early season growth vigor is most likely attributed to slower soil heating temperatures under the wheat straw and wood chip mulch types.

Table 3.4. Early season plant phenology for hops grown at NDSU Horticultural Research Farm, Absaraka, ND in 2018

	BBCH	
	05/11/18	5/18/18
Cultivar (C)		
Cascade	12.7 ns	15.1
Mt. Hood	12.7	15.3
Santiam	12.6	15.3
Mulch (M)		
Landscape	12.9 b	15.3 ab
Wood Chip	12.3 c	15.0 b
Wheat Straw	12.0 c	15.0 b
Control	13.4 a	15.6 a
Nitrogen (N)		
Urea	12.6	15.3
SuperU	12.6	15.2
ESN	12.8	15.2
Source		
C	0.3036	0.1929
M	<.0001 **	<.0001 **
N	0.1030	0.3784
C x M	0.8386	0.0503
C x N	0.3752	0.4523
M x N	0.0405 *	0.9217
C x M x N	0.7633	0.4402

[z] Different letters following means within main effects represent significant differences according to Tukey's HSD ($\alpha \leq 0.05$)

*, ** significant main effects and interactions at $P \leq 0.05$ and 0.01, respectively.

[ns] main effect not significant at $P \leq 0.05$

Bine Height and Surviving Bines

Other growth characteristics were determined at harvest to gauge overall plant vigor and plant responses to treatments and environments. Total height of bines, total number of harvested bines, fresh biomass, and fresh harvest index were recorded at harvest. Fresh biomass and fresh harvest index were recorded in 2018 only. Bine heights between cultivars was significantly different in 2017 and 2018(Table 3.5.). ‘Cascade’ produced significantly taller bines than ‘Mt. Hood’ and ‘Santiam’ in 2017 and 2018. ‘Mt. Hood’ bine lengths were significantly greater than ‘Santiam’ in 2017. Mulch and nitrogen treatments had no significant effect on bine heights in both years. A significant interaction between mulch and nitrogen was reported during analysis in 2018, but it is not considered to be a valid interaction.

Total number of surviving bines at harvest were recorded in 2017 and 2018. These values are critical in understanding the response of cultivars to experiment treatments and if they had an effect on the resulting total bine number at harvest. No significant differences between total bines at harvest were observed in mulch or nitrogen source main effects in 2017 or 2018 (Table 3.5.).Total number of bines at harvest for ‘Cascade’ was significantly greater than ‘Mt. Hood’ and ‘Santiam’, indicating that cascade had higher vigor and was more resilient to in-season bine losses.

Table 3.5. Bine height and total bines harvested for hops grown at NDSU Horticultural Research Farm, Absaraka, ND in 2017 and 2018.

	Bine Length (m)		Total Bines Harvest (Bine $plant^{-1}$)	
	2017	2018	2017	2018
Cultivar (C)				
Cascade	4.9 a[z]	5.7 a	3.63 a	3.86 a
Mt. Hood	4.4 b	5.4 b	3.05 b	3.35 b
Santiam	3.8 c	5.1 b	3.25 b	3.28 b
Mulch (M)				
Landscape Fabric	4.4 [ns]	5.5	3.27	3.56
Wood Chip	4.3	5.4	3.32	3.48
Wheat Straw	4.4	5.3	3.24	3.52
Control	4.3	5.4	3.38	3.41
Nitrogen (N)				
Urea	4.3	5.3	3.37	3.45
SuperU	4.5	5.5	3.25	3.52
ESN	4.3	5.4	3.30	3.53
Source				
C	<.0001 **	0.0011 **	<.0001 **	<.0001 **
M	0.9267	0.7971	0.8261	0.5714
N	0.5055	0.5003	0.6823	0.6696
C x M	0.6578	0.6288	0.0002 **	0.7938
C x N	0.5872	0.7133	0.5809	0.7400
M x N	0.3888	0.0285 *	0.5736	0.2608
C x M x N	0.1597	0.1830	0.3389	0.1357

[z] Different letters following means within main effects represent significant differences according to Tukey's HSD ($\alpha \leq 0.05$)

*, ** significant main effects and interactions at $P \leq 0.05$ and 0.01, respectively.

[ns] main effect not significant at $P \leq 0.05$

Biomass and Fresh Harvest Index

Total fresh biomass (kg plant^{-1}) recorded in 2018, was significant between cultivar at $\alpha \leq 0.05$ (Table 3.6.). Total biomass of 'Cascade' was significantly greater than 'Mt. Hood' and 'Santiam', with 'Mt. Hood' having greater biomass than 'Santiam'. No differences were observed between mulch or nitrogen sources in 2018. No differences in total fresh biomass were observed between main effect interactions in 2018. A fresh harvest index (FHI) was calculated to observe the relationship between total biomass and total fresh yield of hop treatments. Ideally this index would have been created from values corrected for moisture content, however this value was unobtainable due to the total size and complexity of determining accurate dry mass values. A higher harvest index represents a higher ratio of yield component to total plant mass. Significant differences were observed within all main effects for FHI in 2018 (Table 3.6.) The FHI of 'Cascade' was significantly greater than 'Mt. Hood' and 'Santiam' in 2018. Landscape fabric mulch had a significantly greater FHI over wheat straw mulch treatments in 2018. ESN when used as a nitrogen source had a significantly greater FHI than Urea and SuperU in 2018.

Table 3.6. Fresh biomass and fresh harvest index for hops grown at NDSU Horticultural Research Farm, Absaraka, ND in 2018.

	Fresh Biomass (kg plant^{-1})	Fresh Harvest Index
	2018	2018
Cultivar (C)		
Cascade	3.74 a	0.34 a
Mt. Hood	2.28 b	0.16 b
Santiam	1.82 c	0.16 b
Mulch (M)		
Landscape	2.70 ^{ns}	0.25 a
Wood Chip	2.67	0.21 ab
Wheat Straw	2.51	0.20 b
Control	2.56	0.22 ab
Nitrogen (N)		
Urea	2.64	0.21 b
SuperU	2.70	0.21 b
ESN	2.49	0.24 a
Source		
C	<.0001 **	<.0001 **
M	0.6345	0.0024 **
N	0.3080	0.0127 *
C x M	0.6144	0.4766
C x N	0.9418	0.5603
M x N	0.3820	0.4736
C x M x N	0.2846	0.2699

^{z} Different letters following means within main effects represent significant differences according to Tukey's HSD ($\alpha \leq 0.05$)

*, ** significant main effects and interactions at $P \leq 0.05$ and 0.01, respectively.

^{ns} main effect not significant at $P \leq 0.05$

Conclusions

Field research was conducted to evaluate the effect of different mulch types and nitrogen selections and their effect on mature hop systems over multiple years. Mulch selection and nitrogen selection had no significant effect on the yield outcomes of all cultivars evaluated in this study. Differences between cultivars were observed in yield, cone dimensions, bine length, total bines harvested, fresh biomass, and fresh harvest index were also observed. Landscape fabric mulch did produce significantly longer cones and a higher fresh harvest index in comparison to the wheat straw mulch. These metrics suggest that the wheat straw mulch reduce overall vigor during the cone development phase in hop production. Differences between nitrogen sources were only observed in the fresh harvest index, but it did not lead to subsequent increases in yield.

The little differences between mulch and nitrogen treatments suggest that producers have the availability to use various different mulch types and nitrogen sources based off of availability and cost for their systems.

Table 3.7. Rainfall recorded at NDAWN station Prosper, ND 2016-2018

	Rainfall (cm)		
	2016	2017	2018
April	4.31	1.65	0.38
May	8.21	1.68	5.39
June	3.76	8.79	7.93
July	8.79	5.00	6.53
August	2.64	5.26	7.85
September	6.05	15.17	7.09
October	4.86	0.69	6.66
Total	38.62	38.24	41.83

Table 3.8. Accumulated Growing Degree Days May 1st- September 30th, 2017 & 2018 NDAWN Prosper

	GDD	
	2017	2018
May	168	256
June	275	313
July	340	319
August	258	295
September	192	177
Total	1233	1360

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APPENDIX

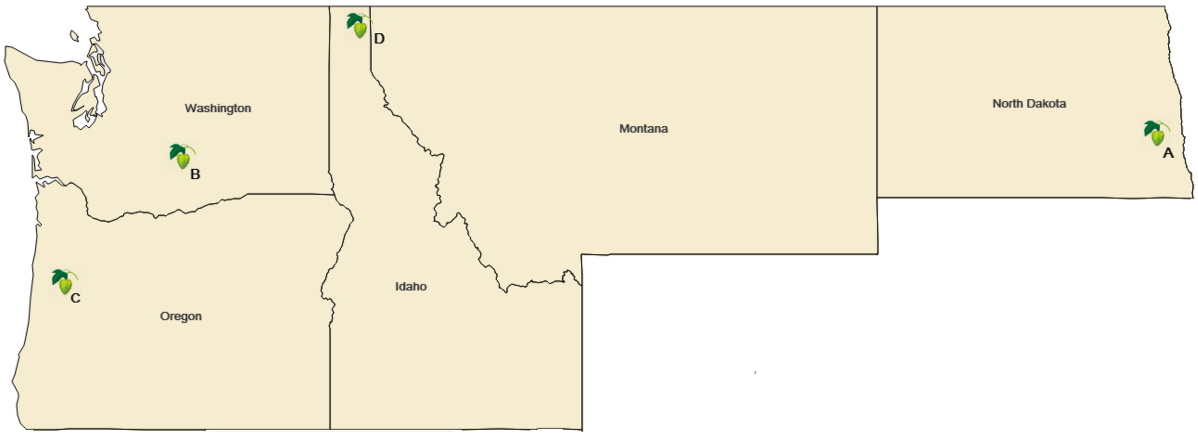

Figure A.1. NDSU eastern hop research yard in relation to major U.S hop growing regions.

A. Absaraka, ND., B- Yakima, WA., C- Corvallis, OR., D- Bonner's Ferry, ID.

Figure A.2. Magnified section of hop bine displaying modified climbing hairs

Figure A.3. Hop rhizomes under landscape fabric mulch