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ABSTRACT

There are increasing acres of land in Connecticut being converted to hop yards as the numbers of breweries increase in the state and want to source local ingredients for their beers. Little has been known about the feasibility of growing hop in Connecticut since the crop was moved to the Pacific Northwest approximately 100 years ago. Therefore, we evaluated hop yield and quality, insect damage, and disease pressure for five cultivars of hop at two locations in Connecticut. Some farmers in the region have shown interest in converting shade tobacco acreage to hop production, so we evaluated the performance of these five cultivars on a low trellis system as well as the traditional high trellis system. Our results show that for some cultivars, such as Cascade, high yields are possible. Two spotted spider mites and potato leaf hoppers were the most damaging insects. Downy mildew was the most damaging disease. The cultivar Cascade produced high yields, high quality, and exhibited tolerance to downy mildew and potato leaf hoppers. Conversion of shade tobacco structure into low trellises for hop may be possible as some cultivars, such as Cascade and Summit, produced similar yields compared to the high trellis. Adequate irrigation is important for healthy, high yielding hop in Connecticut. Overall, we demonstrated that hop can be a viable crop in Connecticut and that pests and diseases can be managed to protect yields and hop cone quality.

INTRODUCTION

Hop (*Humulus lupulus*), also known as common hop, is a dioecious flowering (rarely monoecious), perennial, climbing vine belonging to the *Cannabaceae* (hemp) family (Neve, 1991). Bines can grow 6 to 9 m (20 or more feet) in a single season from rhizomes. Unfertilized cones of female hop are an important agronomic crop as a main ingredient in beer and for use in medicine (Stevens and Page, 2004; Zanoli and Zavatti, 2008). The compounds, resins, essential oils, and polyphenols are responsible for the flavor, the typical bitterness and aroma, and preservation of beer (Mahaffee et al. 2009).

The area in which hop grows is limited to within 35 to 55 degrees latitude. The United States leads in hop production, with 56,683 acres in production in 2017, followed by Germany with production at 48,293 acres (George, 2018). Within the United States, hop production is concentrated in the Pacific Northwest, which harvested about 53,282 acres in 2017 (George, 2018). However, in the last few years hop production has been increasing in states outside of the Pacific Northwest, including the Northeastern United States.

Hop production has a long history in the Northeastern United States. The first settlers brought hop to Massachusetts in 1629 (Neve 1991). The peak of hop production was in the early 19th century, with New York being the main hop growing state (Neve 1991). High downy mildew disease pressure forced growers to resettle the production to the drier conditions of the Pacific Northwest (Neve, 1991). However, hop production in the Northeast is on the rise again due to the increasing popularity of the microbrew culture, local brewpubs, and the growing demand for local/regional products. New York has the largest acreage (400 acres), followed by Massachusetts and Vermont at 25 acres, Maine at 24 acres, New Jersey and Connecticut at 15 acres, and lastly New Hampshire at 2 acres (George, 2018). With the increased production of hop in the Northeast there is a growing need for specific management recommendations adapted to the climate, disease, and pest pressures of this region.

Diseases and pests differ in the Northeast from the Pacific Northwest; possibly due to differences in pathogen strains, climatic conditions, and geographic considerations. Two-spotted spider mite, potato leaf hopper, and hop aphid are the most common insect pests in the Northeast (Caldwerwood et al., 2015; Allan-Perkins et al, 2019a). Two-spotted spider mite (*Tetranychus urticae* Koch) and Damson-hop aphid (*Phorodon humuli* Schrank) can cause serious yield losses in most hop production regions. The two-spotted spider mite is a common pest for more than 180 plant species worldwide (Mahaffee et al., 2009). Populations can increase rapidly during hot and dry weather conditions (Mahaffee et al., 2009). Symptoms appear as a silvery discoloration on leaves which turns reddish brown. Infested cones also appear reddish brown and have reduced yield and quality. The mites produce webbings underneath leaves, which protect them from predators and insecticide spray applications. Damson-hop aphid also causes large economic damage because they reduce plant vigor by defoliation (Calderwood et al., 2015). Aphids can decrease hop yield by directly feeding on cones and by production of a sugary excretion, called “honeydew”, which serves as a medium for sooty mold fungi (Mahaffee et al., 2009; Calderwood et al., 2015). Furthermore, aphids can be vectors for viruses that can cause subsequent damage and losses (Mahaffee et al., 2009).

Potato leafhoppers infest many tree species, ornamentals, and food crops in the United States. They only infest hop in the eastern and midwestern parts of the country but are not problematic in the northwest (Calderwood et al., 2015). The symptoms of leafhopper damage are yellowing of leaf tips and leaf curling, leading to browning of the outer leaf edges in a distinctive “V” pattern called hopper burn. Eventually potato leaf hoppers will cause leaf necrosis, shortening of internodes, stunted growth of the plant, and reduced cone production. Beneficial insects and predators may control small populations, however, when potato leaf hopper densities are high enough, pesticides should be applied that have a low effect on beneficial predators (Mahaffee et al. 2009, Calderwood et al., 2015). An economic threshold level for spraying to control potato leaf hopper has not yet been established for the Northeast, however based on the threshold levels set for other hop growing regions, sprays should be made when two leafhoppers per leaf are present (Darby et al., 2016).

The two most dreaded diseases of hop in the U.S.A. are downy mildew, caused by *Pseudoperonospora humuli*, and powdery mildew, caused by *Podosphaera macularis* (Calderwood et al., 2015). Both pathogens can infect cones, leaves, shoots, and buds and can cause significant crop loss and damage (Mahaffee et al., 2009). Downy mildew mostly affects hop cultivation in humid regions of the U.S.A., such as the Northeast, where high humidity, rainy weather, and temperatures ranging from 46-73°F (8°C-23°C) contribute to increased disease pressure (Gent et al., 2010; Turner et al., 2011). Downy mildew can infect all parts of the plant and infection of cones may lead to 100% yield loss (Mahaffee et al., 2009). The pathogen overwinters in the crown and buds, and spreads with the growth of the plant in spring. Systemically infected shoots, which are called "spikes", appear stunted and chlorotic and have often grey or black sporulation underneath the leaves. These spikes are the primary source for downy mildew epidemics. Symptoms on leaves are angular lesions delimited by veins and sporulation may form on the underside of leaves. Infected cones show brown discoloration and contain less acid content, which leads to a reduction of quality and marketability.

The powdery mildew pathogen, *P. macularis,* overwinters in and on buds and produces infected shoots, called "flag shoots". Characteristic symptoms are white powdery colonies, which can appear on all green parts of the plant as well as raised blisters, chlorotic areas on leaves, and distortion of cones (Mahaffee et al., 2009). The pathogen was confirmed in the Pacific Northwest in 1997 subsequent to the failure of quarantine procedures (Gent et al., 2008b), and now treatment of this disease comprises the majority of fungicide budgets in that area (Turner et al., 2011). It was observed recently in New England, specifically in Connecticut, in 2018 (Allan-Perkins et al., 2019b). Purchasing healthy, disease-free rhizomes and plantlets to avoid introducing diseases in a new hop yard is an important management strategy. A strict and rigorous control management for both downy and powdery mildew is necessary, including sanitation practices like pruning, stripping of lower leaves, removing infested leaves or plants, and weeding. The removal of redundant plant tissues helps to reduce not only diseases but also pests.

In addition to adapting management practices to the unique pests, diseases, and environmental conditions found in Connecticut, another consideration for Connecticut growers is the ability to adapt shade tobacco farms to production of low trellis hop. Connecticut has been known for its production of high quality shade tobacco since the early 1900's, but recently due to high production costs and potential for yield loss Connecticut farmers are producing fewer acres of this crop. The infrastructure for shade tobacco includes wires supported by approximately 2.4 m tall poles onto which shade cloth is affixed (Waggoner and Reifsnyder, 1959). As growers have decided not to plant shade tobacco and as interest in growing hop increases, one possibility is to adapt shade tobacco farms into low trellis hop production.

Low trellis hop production involves growing dwarf or semi-dwarf hop cultivars on poles that are 9.8 ft (3 m) tall, in lieu of growing non-dwarf cultivars on poles between 16.4-26.2 ft (5-8) m tall (Neve, 1991). Hop cones are harvested, while leaving the bines intact, either by the use of an over-row mechanical harvester or by hand (Neve, 1991). This removes the need to provide new string or wire supports for hop each year as the next years' bines will grow in a hedge-like manner over the plant material left from the previous season. Although this can reduce labor costs for stringing and may have some benefits for disease management (Turner et al., 2011), it requires significant up-front cost to purchase a special over-row mechanical harvester or to increase labor costs for hand-picking. Additionally, dwarf cultivars of hop are not widely available to commercial growers in the United States at this time. Therefore, we tested how non-dwarf cultivars and a semi-dwarf variety grow on existing shade tobacco structures and respond to high trellis harvesting that involves removing the bines each year to see if these practices could be readily adapted by Connecticut growers.

The objective of this research was to investigate the feasibility of growing hop in Connecticut on high trellis and converted shade tobacco low trellis systems, and if the hop cones display equal quality and yield to industry standards. Experiments were conducted over five years and, yield, quality, and susceptibility to diseases and pests of five cultivars were analyzed at two locations. The results of this study provide Connecticut growers with practical information on growing hop in this region, how cultivars may differ in growth characteristics compared to other growing regions, and additional management strategies that need to be leveraged to improve hop yield and flavor.

MATERIALS AND METHODS

Hop Cultivation

Hop plantings were established in 2013 in plots at the Valley Laboratory in Windsor and Lockwood Farm in Hamden, Connecticut. Hills were established with one plant of a rooted, actively growing cutting obtained from the New York State Clean Hops Program. Cuttings were planted 3.2 ft (1 m) apart within each row with 9.8 ft (3 m) between the rows, for an equivalent of 1,200 crowns per acre. Two rows of high trellis were established at a height of 17 ft (5.2 m) at the Valley Laboratory and a height of 18ft (5.5 m) at Lockwood Farm. Two rows of low trellis were established at a height of 9.8 ft (3 m) at the Valley Laboratory and the Lockwood Farm. Each plot contained five hills and plots were arranged in randomized block design with 2 to 3 replicates per row. Five cultivars of hop were chosen to evaluate on both high and low trellis: AlphAroma, Cascade, Newport, Perle, and Summit.

AlphAroma, also called Rakau, is a dual-purpose hop, meaning it is used for both bittering and aroma with moderate resistance to downy mildew (Healey, 2018; USDA ARS, 2018). Cascade is an aroma hop and is used in a wide variety of beer styles making it one of the most grown and utilized hops in the United States (USAHops, 2018). Cascade has moderate root stock resistance to downy mildew, but is susceptible to powdery mildew (Neve, 1991; USDA ARS, 2018). Newport is a bittering hop and is resistant to both downy and powdery mildew (Henning et al., 2004). Perle is a dual-purpose hop with moderate resistance to downy mildew and is susceptible to powdery mildew (Neve, 1991; Healey, 2018). Summit is a semi-dwarf variety (Jeske, 2007), potentially making it well suited to low trellis hop production. It is a bittering hop with resistance to powdery mildew, but is moderately susceptible to downy mildew (Jeske, 2007). Five plots of AlphAroma, Cascade, Newport and Perle were planted on the high trellis system at Lockwood Farm and Valley Laboratory hop yards, with the exception of four plots of Newport and one plot of Summit at the Valley Laboratory. Four plots of AlphAroma, Cascade, Newport, Perle, and Summit were planted on the low trellis systems at both locations.

Each spring hop trellises were strung using heavy duty 9 lb (4.08 kg) sisal baler twine. Plots were maintained with spring training, fertilization, and a range of fungicide treatments from 2013-2017 to allow evaluation of disease susceptibility while maintaining relatively low levels of disease (Table 1). In 2018, an initial fungicide application in early spring, and fungicide and insecticide applications throughout the growing season based on detection of pathogens and pests was used to demonstrate effective IPM of pathogens and pests (Table 1). Weeds surrounding the hop plants were managed using a combination of herbicides, mechanical and hand removal throughout the growing seasons. Mulch was added to the hop rows at the Valley Laboratory in May and June of 2016. Leaves on the lower 1 m (3 ft) of each bine were removed either by hand or using herbicide every year (Table 1). Irrigation was supplied as needed by drip irrigation lines in 2014, 2016, 2017, and 2018 and by overhead irrigation in 2013 and 2015 at the Valley Laboratory and by drip irrigation in 2018 at Lockwood Farm. Throughout the growing season plants were evaluated for the presence of disease or insect pests at both locations. In 2016, 2017, and 2018, around the summer solstice, two of the low trellis plots for each cultivar were "topped" by pruning the bines within 0.3 m (1 ft) from the top wire at Valley Laboratory. Plots were topped similarly at Lockwood Farm only in 2018.

In August and September, depending on the cultivar, the cones were harvested by hand in 2013-2016 and by mechanical harvester (Hopster5P, Hop Harvester LLC, NY) in 2017 and 2018 (Table 1). Only the inner three plants within each 5-crown replicate plot were harvested to avoid mixing of cultivars in the final sampling. The cones were dried on a screen at the Valley Laboratory at ambient temperature and at Lockwood Farm in a hop dryer for three to seven days depending on the humidity, until they reached 10-12% dry matter. The hops were vacuum packed and stored at 39°F (4°C).

Data collection

Weather data was collected annually at each hop yard using National Weather Service COOP automatic weather stations with the data being accessed at the Connecticut Agricultural Experiment Station website (https://portal.ct.gov/CAES/Weather-Data/Weather/Weather-Data) and growing degree days were calculated based on 50°F (10°C) and accessed from the same website. Soil nutrients and edaphic properties were tested in 2014 from the Valley Laboratory, 2016 for Lockwood Farm, and both hop yards in 2017 at the Connecticut Agricultural Experiment Station. The weight of hop cones collected per crown was measured and converted from grams per cone to pounds per acre based on planting densities of 1200 crowns per acre. The weights were reported as pounds per acre at 10% moisture, being converted from dry matter content calculated per variety and trellis height at time of harvest. Hops were harvested at Valley Laboratory Farm from 2014-2018 for all cultivars, except Perle in 2017 and 2018 and AlphAroma in 2018 due to poor growing bines. At Lockwood Farm, hops were harvested from 2016-2018 for all cultivars except Perle in 2018 due to poor growth. Quality analysis of yield and acid content was conducted by the VT Crops and Soils Hops Quality Testing Lab at the University of Vermont (Burlington, VT) in 2015 and 2016 and by Surveillant LLC (Old Lyme, CT) in 2017 and 2018. Quality analysis was not performed in 2013 or 2014. The hop yards were scouted for disease every 2-4 weeks, depending on disease pressure. Downy mildew incidence was recorded as infected basal spikes early in the season and symptomatic leaf tissue later in the season from 2014-2018 at the Valley Laboratory hop yard and in 2016 and 2017 at the Lockwood Farm hop yard. Potato leaf hopper damage was recorded for plants showing symptoms, such as leaf chlorosis beginning at edge of tissue (hopper burn), and signs, specifically presence of leaf hoppers on the leaf underside, for both hop yards in 2015, 2017, and 2018 and for only the Valley Laboratory hop yard in 2016.

Data analysis

Data was analyzed for statistical differences by analysis of variance (ANOVA) using the generalized linear mixed model (GLIMMIX) with the program SAS Studio University Edition (SAS Institute, Cary, NC) as shown in Tables 2-7. Due to the data being unbalanced a full factorial design of all effects could not be performed. Yield between hop yards, among years, and for the interaction of hop yard × year was tested with blocks as the random effect. The effect of cultivar and year were analyzed within hop yard in a full factorial design with block as the random variable. Comparisons among yields for trellis height and year were made in a full factorial design within cultivar and hop yard with trellis height and year as fixed variables and block as the random variable. Since only replicate block of Summit was grown on the high trellis at the Valley Laboratory hop yard and Summit was only grown on the low trellis at the Lockwood Farm hop yard, the effect of trellis height could not be estimated for this cultivar.

The pruning study was only conducted in 2016-2018 at the Valley Laboratory hop yard and 2018 at the Lockwood Farm hopyard, therefore differences in yield for pruned versus unpruned bines on the low trellis system were compared for variables cultivar and pruning as fixed variables and block as the random variable in a full factorial design.

Potato leaf hopper damage was evaluated using different rating scales each year, therefore potato leaf hopper damage was assessed within years for main effects cultivar, hop yard, and, trellis height as a full factorial design with blocks as the random variable. Downy mildew disease severity was assessed using cultivars, trellis heights, and years as main effects and blocks as the random effect as full factorial design within hop yards. For all tests, the means from significant interactions (p>0.05) were further separated using the Tukey-Kramer model.

RESULTS

Weather data

The warmest average temperatures for March-August occurred during 2016 and 2018 at both locations (Figure 1). The greatest number of degree growing days throughout the season were in 2016 and 2017 on both hop yards, but 2015, 2016, and 2018, had the highest cumulative degree days by the end of the season (Figure 2). Cumulative rainfall was highest in 2017 for the Valley Laboratory hop yard and in 2018 for Lockwood Farm (Figure 3). The lowest amount of rainfall was in 2015 for both hop yards (Figure 3).

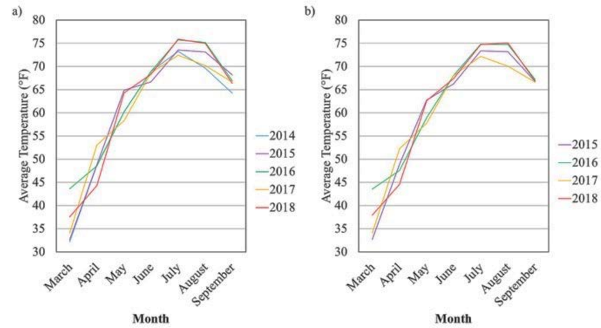

Figure 1. Monthly mean temperature (°F) for a) Valley Laboratory hop yard and b) Lockwood Farm hop yard.

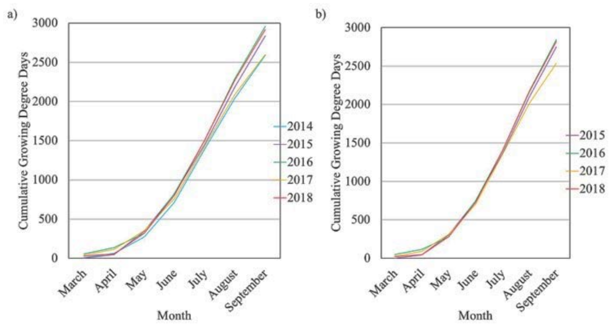

Figure 2. Monthly mean degree days (based on 50°F) at a) Valley Laboratory hop yard and b) Lockwood Farm hop yard.

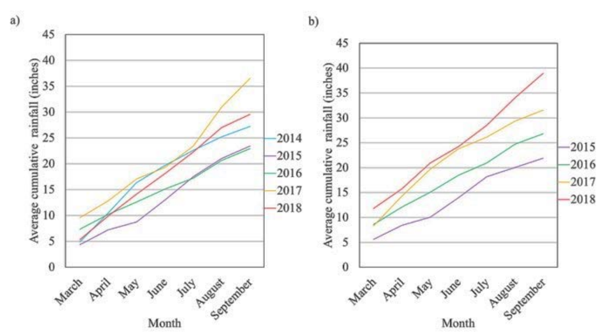

Figure 3. Monthly cumulative rainfall (inches) for a) Valley Laboratory hop yard and b) Lockwood Farm hop yard.

Soil nutrients and edaphic properties

In 2014, soil testing for the Valley Laboratory hop yard found the soil was sandy loam for the high trellis and loamy sand for the low trellis, both with medium high organic matter. The pH was 5.8 and 5.7 for high and low trellis, respectively, and nitrate nitrogen was 1 ppm, ammonium nitrogen 12 ppm, phosphorous 100 ppm, and potassium over 250 ppm. In 2016 the Lockwood Farm hop yard had sandy loam soil type, pH 5.9, and medium high organic matter. Nitrate nitrogen was1 ppm, ammonium nitrogen at 24 ppm, phosphorous at 50 ppm, and potassium over 250 ppm. In 2017, both hop yards had a slight increase in pH (6.1 and 6.3 for the Valley Laboratory low and high respectively and 6.1 and 6 for Lockwood Farm low and high trellises, respectively). At the Valley Laboratory, the nitrate nitrogen remained at 1 ppm, the ammonium nitrogen reduced to 6 ppm, phosphorus decreased to 50 ppm for low trellis and remained at 100 ppm for the high trellis, and potassium remained at over 250 ppm. For Lockwood Farm, nitrate nitrogen increased to 3 ppm, ammonium nitrogen decreased to 6 ppm, phosphorus decreased to 38 ppm for low trellis and increased to 100 ppm for high trellis, and potassium remained at over 250 ppm. Soil properties were not tested in 2018.

Yield

Average hop yield across all varieties generally increased with each successive year of growth, except for a decline from 2014 to 2015 at the Valley Laboratory hop yard and from 2017 to 2018 at the Lockwood Farm hop yard (Figure 4). In 2016 and 2017, Lockwood Farm had a significantly higher hop yield than the Valley Laboratory hop yard, but the Valley Laboratory had a significantly greater yield in 2018 (Figure 4, Table 3).

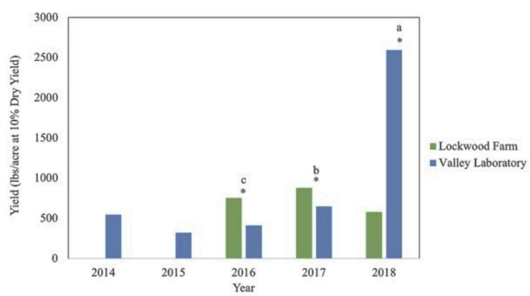

*Figure 4. Hop yields (lbs per acre at 10% dry weight) averaged across all cultivars for each year and hop yard. Lower case letters represent statistically significant differences among years as determined by analysis of variance and least mean separation using Tukey-Kramer HSD at p<0.0001. * indicate statistically significant differences between hop yards within a year as determined by analysis of variance and least mean separation using Tukey-Kramer HSD at p<0.0001.*

At Lockwood Farm, Cascade and Summit produced the highest yields averaged from both hop yards in all years (Figure 5, Table 4). Perle had the lowest yields averaged across both hop yards in all years, and in 2018 yields were too poor to harvest. AlphAroma had the second lowest yields except in 2018 when Perle was not measured and Newport was equally low (Figure 5, Table 4). At the Valley Laboratory hop yard, Cascade tended to have the highest yields, but only statistically so in 2016 and 2017 (Figure 6, Table 4). Summit had statistically similar yields to Cascade in 2014. Perle tended to have the lowest yields, but not statistically significantly so, and was not able to be harvested in 2017 and 2018 due to poor production (Figure 6, Table 4). There were no significant differences among harvested cultivars in 2018.

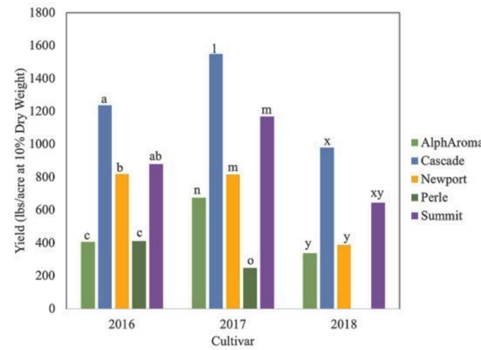

Figure 5. Hop yields (lbs per acre at 10% dry weight) averaged for Lockwood Farm hop yard for each cultivar and year. Lower case letters represent statistically significant differences among cultivars within each year as determined by analysis of variance and least mean separation using Tukey-Kramer HSD at p=0.0101.

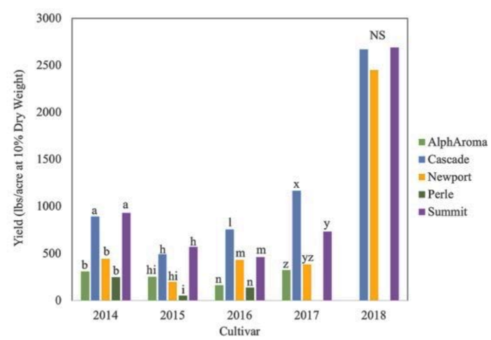

Figure 6. Hop yields (lbs per acre at 10% dry weight) averaged for Valley Laboratory hop yard for each cultivar and year. Lower case letters represent statistically significant differences among cultivars within each year as determined by analysis of variance and least mean separation using Tukey-Kramer HSD at p=0.0117.

The high trellis tended to have greater yields for all cultivars on both Lockwood Farm and Valley Laboratory hop yards (Figures 7 and 8, Table 4), but only statistically significantly for AlphAroma in all years and at both hop yards, Cascade at both hop yards in 2017, and Newport at Valley Laboratory hop yard in 2014, 2016, and 2017 (Figures 7 and 8, Table 4). Pruning the last 12 inches off the low trellis bines did not significantly affect yield compared to unpruned bines for any cultivar (Figure 9, Table 5).

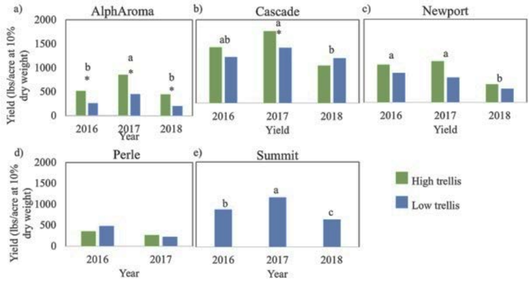

*Figure 7. Hop yields (lbs per acre at 10% dry weight) averaged across both hop yards for each cultivar and each year at Lockwood Farm for high and low trellis systems for cultivars a) AlphAroma, b) Cascade, c) Newport, d) Perle, and e) for year on the low trellis for the cultivar Summit. Lowercase letters represent statistically significant differences among years and an * represents statistically significant differences between high and low trellis as determined by analysis of variance and leas mean separation using Tukey-Kramer HSD at p<0.05.*

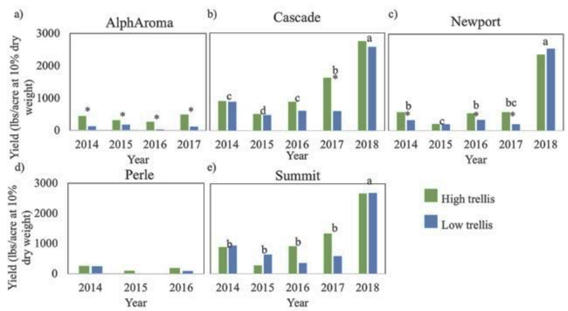

*Figure 8. Hop yields (lbs per acre at 10% dry weight) averaged for each year at Valley Laboratory for high and low trellis systems for cultivars a) AlphAroma, b) Cascade, c) Newport, d) Perle, and e) Summit. Lowercase letters represent statistically significant differences among years and an * represents statistically significant differences between high and low trellis as determined by analysis of variance and leas mean separation using Tukey-Kramer HSD at p<0.05.*

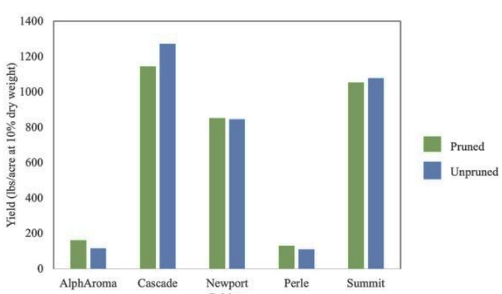

Figure 9. Hop yields (lbs per acre at 10% dry weight) for pruned and unpruned low-trellis hop averaged across both hop yards for each cultivar. There was no significant difference as determined by analysis of variance at p<0.05.

Acid Content

For most cultivars, the percentage of alpha and beta acids was within the industry expected range (USAHops, 2018). Alpha and beta acids for AlphAroma were in the industry range in all years (Figure 10). For Cascade hops, alpha acid content was higher than expected in 2015 and in 2016 for Valley Laboratory low trellis, 2017 for Lockwood Farm low trellis, and 2018 for Lockwood Farm high trellis (Figure 11). Beta acid content was generally higher for Cascade than the industry range in all years and hop yards, except for Valley Laboratory high trellis in 2017 and Lockwood Farm low trellis in 2018 (Figure 11). Newport and Perle hops were generally lower than the industry standard in all years, except for Perle beta acids in 2016 (Figures 12 and 13). The alpha acid content for Summit was within range in 2015 and 2016 and was lower than the industry standard in 2017 and 2018 (Figure 14). Beta acid content was within the industry standard for Summit on all sampling dates, except for the Valley Laboratory low trellis in 2017 and the Valley Laboratory high and low trellis in 2018 (Figure 14).

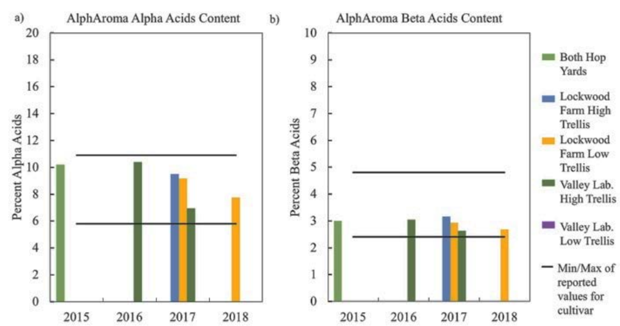

Figure 10. Mean a) alpha and b) beta acid content for AlphAroma hops for each hop yard, trellis height, and year. Black bars represent minimum and maximum expected values based on the Industry Standard Range.

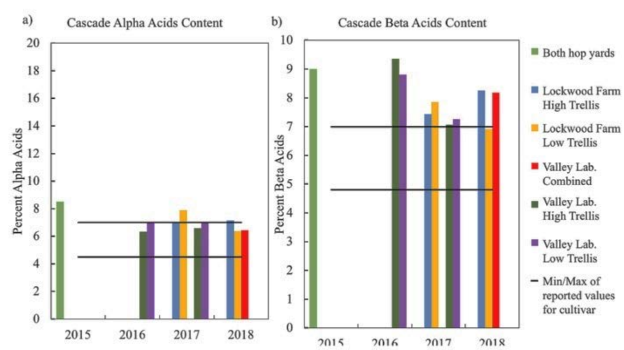

Figure 11.Mean a) alpha and b) beta acid content for Cascade hops for each hop yard, trellis height, and year. Black bars represent minimum and maximum expected values based on the Industry Standard Range.

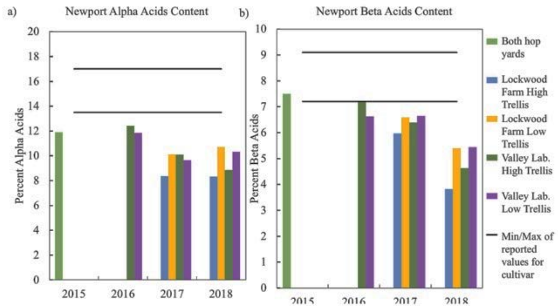

Figure 12. Mean a) alpha and b) beta acid content for Newport hops for each hop yard, trellis height, and year. Black bars represent minimum and maximum expected values based on the Industry Standard Range.

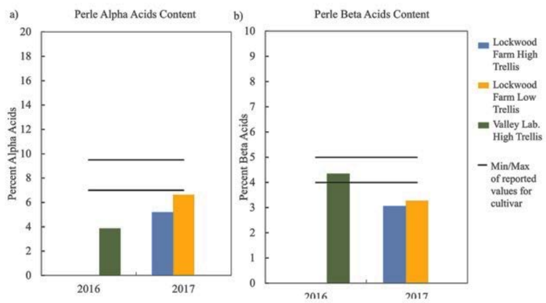

Figure 13. Mean a) alpha and b) beta acid content for Perle hops for each hop yard, trellis height, and year. Black bars represent minimum and maximum expected values based on the Industry Standard Range.

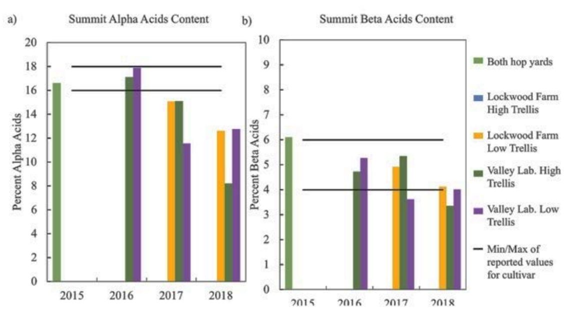

Figure 14. Mean a) alpha and b) beta acid content for Summit hops for each hop yard, trellis height, and year. Black bars represent minimum and maximum expected values based on the Industry Standard Range.

Insect Damage

Aphids were present starting in 2014 at the Valley Laboratory hop yard and 2016 at the Lockwood Farm hop yard but remained at low levels throughout the study. In 2016, there were hop flea beetles at low levels at the Valley Laboratory. Fall webworm was detected in the Valley Laboratory plots in 2014, 2017, and 2018 at very low levels. The insect pests that caused the most damage on hop at both hop yards were two-spotted spider mites and potato leaf hoppers. The spider mites were damaging on all hop cultivars, especially younger plantings. The potato leaf hoppers tended to be most damaging on the cultivars Newport and Perle, statistically significantly so at Lockwood Farm in 2015 and 2018 and Valley Laboratory in 2016 (Figure 15, Table 5). In 2015, Summit was as damaged as Newport and Perle at Valley Laboratory. Cascade had the least damage at Lockwood Farm in 2015 and 2018, Valley Laboratory in 2016, and Cascade and AlphAroma had the least damage at Valley Laboratory in 2015 (Figure 15, Table 5). Potato leaf hoppers were not detected on hop in 2017 at both hop yards and not detected at the Valley Laboratory in 2018.

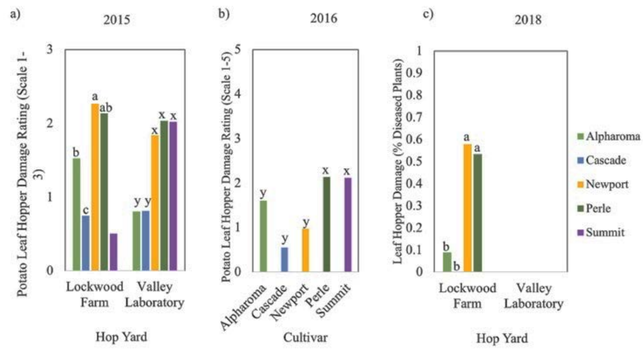

Figure 15. Potato leaf hopper damage across for both hop yards for each cultivar in a) 2015 for both hop yards, b) 2016 for Valley Laboratory, and c) 2018 for both hop yards. Lower case letters represent statistically significant differences among cultivars within a hop yard as determined by analysis of variance and least mean separation using Tukey-Kramer HSD at p<0.05. There was no detected leaf hopper damage in 2017.

Disease Severity

There were significant differences in disease severity of downy mildew among cultivars (Table 6). AlphAroma tended to be the most infected cultivar in all years (Figure 16), but was statistically significant in 2016 and 2017 at Lockwood Farm hop yard and in 2015 along with Newport at Valley Laboratory hop yard. Powdery mildew was not detected on any of the cultivars on either hop yard in any year. A new fungal disease, Diaporthe leaf spot caused by *Diaporthe humulicola*, was found on all cultivars of hop on both hop yards in 2018 and affected both leaves and cones (Allan-Perkins et al., 2020). Further investigation into this new disease is ongoing at the Connecticut Agricultural Experiment Station.

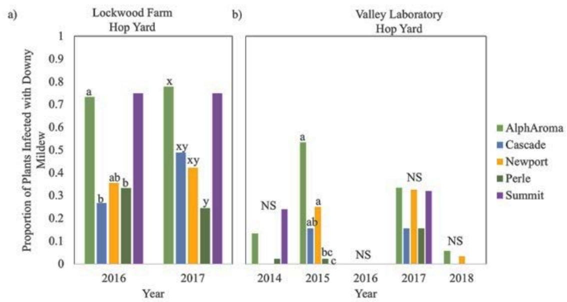

Figure 16. Percent of plants affected by downy mildew across each cultivar and year for a) Lockwood Farm and b) Valley Laboratory hop yards. Lower case letters represent statistically significant differences among cultivars within years as determined by analysis of variance and least mean separation using Tukey-Kramer HSD at p≤0.05 and NS indicates no significant differences p>0.05.

DISCUSSION

The results of this five-year study demonstrate that it is feasible to grow hop in Connecticut and produce high quality and yields of hop cones to be used for brewing. Hop growth and aroma characteristics are influenced by many factors, such as climate, soil, sun, rainfall and irrigation, fertilization, and pest and disease management. In 2016 and 2017, hop yields were greater at the Lockwood Farm than Valley Laboratory, potentially due to the difference in soil texture and irrigation at the two sites. The Valley Laboratory hop yard has slightly sandier soil than Lockwood Farm. Water retention at the Valley Laboratory hop yard would be lower than at Lockwood Farm and therefore in drier years the Valley Laboratory hop yard would be expected to have lower yields due to reduced water availability to the hop plants. In 2015, the hop bines from the Valley Laboratory had a very low yield compared to the other years, potentially due to the absence of irrigation that year and the low amount of rainfall. In 2018, the yield at the Valley Laboratory hop yard exceeded that of Lockwood Farm. This may have been due to the increased rainfall during July and September at the Valley Laboratory, which along with irrigation, may have met the water requirements for the hop and allowed them to have higher yields than previous years which had lower monthly rainfall amounts in July and August.

There was significant damage from a large population of potato leaf hoppers at the Valley Laboratory in 2015 which may have contributed to the decrease in yield from 2014 to 2015, instead of the expected increase. High pressure from this insect may also have contributed to the lower yield at Lockwood Farm compared to Valley Laboratory in 2018, when Lockwood Farm which had high amounts of leaf hopper damage with little damage reported from the Valley Laboratory.

Hop trials in Vermont (averaged over five years from 2011-2016) had lower yields compared to the Pacific Northwest industry standard ranges (Darby et al. 2016). Compared to the average yields in Vermont, Connecticut projected yields (lbs/acre at 10% dry weight) are higher and closer to industry standards for Cascade. Specifically, Cascade average yield in Vermont was 468 lbs/acre, Connecticut yields were 1236 lbs/acre at Lockwood Farm and 753 lbs/acre at Valley Laboratory hop yard in 2016, and the Pacific Northwest reported 1636.33 lbs/acre that year (Darby et al., 2016; George, 2018). In 2018, yields for Cascade at Valley Laboratory hop yard were higher than those reported for the Pacific Northwest at 2667.8 versus 1770.33, respectively. Summit was not included in the Vermont study. In 2016 and 2017, Connecticut yields of Summit were lower than those reported for the Pacific Northwest (879.2 at Lockwood Farm and 461.1 at Valley Laboratory compared to 1648 and 1168.5 at Lockwood Farm and 731.2 at Valley Laboratory compared to 2067) but in 2018 they exceeded those reported in the Pacific Northwest at 2687.1 lbs/acre at the Valley Laboratory hop yard versus 1826 lbs/acre (George, 2018), however at the Lockwood Farm hop yard yields were only 644.6 lbs/acre.

Newport and Perle were also tested in the Vermont study (Darby et al. 2016). The average yield from 2011-2016 was 395 lbs/acre and 178 lbs/acre respectively. In Connecticut in 2016, Newport yields were 818 lbs/acre at Lockwood Farm and 431.4 lbs/acre at the Valley Laboratory hop yard. Perle was not harvested in 2018 at Lockwood Farm or in 2017 and 2018 at Valley Laboratory hop yard because of poor hop quality and yields. In 2016, only 411 lbs/acre were harvested at Lockwood Farm and 137.2 lbs/acre harvested at Valley Laboratory hop yard, compared to 1164 lbs/acre in PNW (George, 2018). Differences in the yields between Vermont and Connecticut in 2016 may appear greater since the Vermont yields were reported as the average over five years and may have been greater in 2016.

The lower yields in Connecticut and Vermont versus the Pacific Northwest prior to 2018 could reflect the age of the hop, since hop bines are estimated not to produce 100% of the yield potential until year 4 or 5 of growth (Sirrine et al., 2014). The slightly warmer climate of Connecticut versus Vermont may have increased hop yield in the more southern state. These results also highlight that cultivar adaptability to climate is an important consideration. The cultivar Perle, originally from Germany, did not produce well in the Vermont or Connecticut studies, possibly due to poor adaption to temperatures or moisture in the Northeast. The variability in hop yields between hop yards reflects the importance of consistent irrigation and disease and pest management to improve hop yield of any cultivar. For some cultivars, such as Cascade and Summit in this study, we see the possibility to have yields equivalent to the Pacific Northwest.

Hop quality, as measured by alpha and beta acids, was within the industry standard ranges for most cultivars in most years. Cascade had higher than expected alpha acid content in 2015 at both hop yards and on Lockwood Farm low trellis in 2017 and high trellis in 2018 and higher than expected beta acid content in all years except the Lockwood Farm low trellis in 2018. It has been anecdotally reported that Cascade hops grown in Connecticut have a slightly different flavor profile than those grown in other regions, which potentially could be due to these variations in alpha and beta acid content.

Newport had lower than expected acid contents in all years for all hop yards, as did Perle in 2016 and 2017 (except 2016 for the Valley Laboratory hop yard for beta acids) and Summit was usually below the industry standard ranges (except for 2015 and 2016) for alpha acids and usually within range for beta acids (except for the Valley Laboratory low trellis in 2017 and high trellis in 2018). The differences in acid content may be due to different soil types, weather conditions, or disease pressures facing hop throughout the growing season or from different cone maturity at harvest time. Further testing into the specific acid content would reveal more indications of flavor profile for hop but should be made for each hop harvest since predictions on hop flavors each year would be difficult to make purely based on region, due to potential differences yearly based on weather and harvest time.

The conversion of shade tobacco farms into low trellis hop yards is of interest to Connecticut growers. Statistically, we found no difference in yield within a cultivar whether it was grown on high or low trellis. Although, in some years and for some cultivars, yield was greater on the high trellis, specifically 2.7×'s greater in 2017 for Cascade, 4.2×'s greater for AlphAroma in 2017, and 2.3×'s greater for Summit, the semi-dwarf variety in 2017 at Valley Laboratory hop yard. Therefore, growers should be able to grow high yields of hops on low trellis, but if possible to set up high trellis system there may be better production overall. The first three years of our experiment to determine if pruning one foot off the top of bines would increase hop yield on the low trellis shows no statistical differences. However, for highly productive cultivars, specifically Cascade, bine pruning may increase yield, as it did in 2016 and 2017 by 1.5×'s the unpruned yield. In 2018, hop yields were so great there was no difference from bine pruning, which may indicate this process is only beneficial during establishment years or when water is limited. For cultivars with poorer vigor and yields, such as AlphAroma and Perle, pruning the bines reduced hop yield. The effects of bine pruning on the low trellis will continue to be evaluated at the Valley Laboratory and Lockwood Farm hop yards by the Connecticut Agricultural Experiment Station.

Not only do yields and acid characteristics of the same cultivar differ from one region to another region but also diseases and pests can vary (Neve, 1991, Calderwood et al., 2015). The insect and disease pressures on Connecticut hop are similar to those reported in Vermont, specifically two spotted spider mites, potato leaf hoppers, and downy mildew (Calderwood et al., 2015). There were differences in cultivar susceptibility to potato leaf hopper damage in this study. In 2015, 2016, and 2018, Cascade was least affected by potato leaf hopper damage. This is similar to the results in Vermont, in which Cascade had lower potato leaf hopper presence compared to other cultivars, including Perle and Newport, although it was not statistically significant (Darby et al, 2017). Further studies are needed to evaluate hop cultivars for susceptibilities to potato leaf hopper in Connecticut.

Although powdery mildew has been reported in Connecticut (Allan-Perkins et al., 2019b), it was not detected on either hop yard during the course of this study, suggesting the return of powdery mildew is not widespread in the area at this time. However, growers should continually monitor for this disease to prevent its establishment in hop crowns on their hop yard. Downy mildew was detected on all hop cultivars (except Summit in 2014) on years without an early spring application of mefenoxam. Applying a preventative fungicide spray did reduce downy mildew presence to below detectable levels on Cascade, Perle, and Summit, and decreased by 89.2% on AlphAroma and 94.5% Newport from 2017 to 2018. In Connecticut, this early spring soil drench application is important to controlling downy mildew throughout the season. The use of this fungicide will need to be monitored as resistance development to mefenoxam has been reported in *P. humuli* isolates in the Pacific Northwest (Gent et al., 2008a).

All five cultivars grown in this study are considered moderately resistant to downy mildew, with Cascade having moderate root stock resistance but moderate susceptibility in shoots. In our study, AlphAroma had high infection rates in all years, and was one of two cultivars that showed symptoms in 2018, suggesting it was not resistant to the downy mildew isolates that occurred in the two hop yards in this study. Cascade tended to have lower infection than the other cultivars in all years, which is consistent with the reported relationship for hop with resistance to crown rot having a reduced number of infected basal spikes in subsequent years (Johnson and Anliker, 1985).

CONCLUSIONS

Hop can be grown commercially in Connecticut and production quality and yields can be similar to that of other hop growing areas within the United States. Cascade seems to be the best adapted cultivar to Connecticut that we tested, producing high yields and quality and tolerance to downy mildew and potato leaf hoppers. Converting trellises previously used for shade tobacco production may be viable for hop growing, especially for certain cultivars such as Cascade and Summit. However, hops grown on low trellis systems may be more difficult to harvest with commercial hop combines due to bines wrapping around the top wire. Irrigation is an especially important component of hop growing in Connecticut, as adequate moisture produces greater hop yields. Overall, the return of commercial hop yards to Connecticut can be a viable business for the state that can help meet the demand for locally grown hops for local craft breweries and farm breweries.

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Table 1. Management practices at the Valley Laboratory hop yard and Lockwood Farm hop yard from 2013-2018.

	Valley Laboratory Hop Yard						Lockwood Farm Hop Yard			
	2013	2014	2015	2016	2017	2018	2015	2016	2017	2018
Spring Pruning	NA	Apr 28	Apr 21 and May 6	May 11				May 5		
Initial Training	NA	May	May 18	May 20	May 8-12	May 11, 14, 16	June 11 and 19	May 5, 12, 18	May 3-18	May 15 and 18
Stripping Bines	NA	NA	Jul 17 and 20: by hand	May: Flumioxazin (Chateau, Valent)		June 20: Flumioxazin (Chateau, Valent)		By hand	June 26: Flumioxazin (Chateau, Valent)	June 28: Flumioxazin (Chateau, Valent)
Fertilization (lbs N/acre)	NA	May 13: 29	May 26: 36	Apr 19: 50	Apr 18: 75	May 21: 100	June 5: 70	Apr 22: 50	Apr 27: 75	
		Jun 4: 50	May 28: 36	May 13: 35 (High trellis only)	May 12: 50	June 11: 50		May 27: 25	June 23: 50 (new plants) and 25 (established plants)	May 23: 100
		Jul 8: 25	Jul 6: 35	May 19: 100	June 9: 50	July 24: 30		June 30: 50	July 27: 25 (new plants)	
		Jul 15: 25		May 23: 35	June 19: 25				July 28: 25 (established plants)	
				June 30: 50	July 5: 25					
				July 18: 50						
Fungicide Applications	July 24: Dimethomorph (Forum, BASF)		July 20: Dimethomorph (Forum, BASF)		May 12: Dimethomorph (Forum, BASF)	Apr 25: Mefenoxam (Ridomil Gold, Syngenta)	June 28 Mandipropamid (Revus, Syngenta)	May 9: Fluopicolide (Presidio, Valent) and Potassium phosphite (Prophyt, Helena)	April 27: Mefenoxam (Ridomil Gold, Syngenta)	April 27: Mefenoxam (Ridomil Gold, Syngenta)
	Aug 16: Famoxadone/ Cymoaxanil (Tanos, DuPont) and Mandipropamid (Revus, Syngenta)					May 17: Dimethomorph (Forum, BASF)		June 27: Fluopicolide (Presidio, Valent) and Potassium phosphite (Prophyt, Helena)	June 16: Pyraclostrobin and Boscalid (Pristine, BASF)	May 29: Dimethomorph (Forum, BASF) and Potassium phosphite (Prophyt, Helena)
Insecticide Applications	July 24: Abamectin (Avid, Syngenta)		June 12: *Amblyseius andersoni* mites for TSSM		June 6: Imidacloprid (Admire, Bayer)	May 31: UF oil for TSSM	June 19: *Amblyseius andersoni* mites for TSSM	June 27: Imidacloprid (Admire, Bayer)	June 16: Imidacloprid (Admire, Bayer)	June 17: Imidacloprid (Admire, Bayer)

		Aug 16: Spinetoram (Delgate, Dow)				July 7: Spinetoram (Delegate, Dow), Imidacloprid (Admire, Bayer), and Etoxazole (Zeal, Valent)	June 8: Imidacloprid (Admire, Bayer) preventative for PLH				7/20 Imidacloprid (Admire, Bayer), Pyrethrins (PyGanic, Valent), and Etoxazole (Zeal, Valent)
Harvest Date	Newport		Aug 5 and 8	Aug 19 and 24	Aug 26	Sep 1	Aug 28	Sep 2	Sep 8	Aug 23	Aug 21
	Perle		Aug 11 and 12	Aug 25	Aug 29				Sep 12	Aug 30	
	Cascade		Aug 12 and 14	Aug 19 and 25	Aug 29	Sep 1	Aug 27	Sep 2	Sep 8	Aug 28	Aug 21
	Summit	Aug 23	Aug 22	Aug 19 and 24	Sep 2	Sep 5	Aug 28	Sep 2	Sep 8	Aug 28	Aug 21
	AlphAroma		Sep 5 and 9	Sep 8 and 9	Sep 22	Sep 5		Sep 2	Sep 20	Aug 30	Sep 4

NA= not applicable; TSSM= two spotted spider mites; PLH=potato leaf hopperx

Table 2. Significance of p values for the effect of hop yard and year on average hop yield as lbs/acre at 10% dry weight as determined by analysis of variance

	p value
Hop yard	<0.0001
Year	<0.0001
Hop yard × Year	<0.0001

Table 3. Significance of p values for the effect of cultivar and year on average hop yield as lbs/acre at 10% dry weight for each hop yard as determined by analysis of variance

	Lockwood Farm	Valley Laboratory
Cultivar	<0.0001	<0.0001
Year	0.0002	<0.0001
Cultivar × Year	0.0101	0.0117

Table 4. Significance of p values for the effect of trellis height and year on average hop yield as lbs/acre at 10% dry weight for each hop yard as determined by analysis of variance

	AlphAroma		Cascade		Newport		Perle		Summit	
	Lockwood Farm	Valley Laboratory	Lockwood Farm	Valley Laboratory	Lockwood Farm	Valley Laboratory	Lockwood Farm	Valley Laboratory	Lockwood Farm	Valley Laboratory
Trellis Height	0.0072	0.0075	NS	0.0272	NS	0.0472	NS	NS	NA	NA
Year	0.001	NS	0.0171	<0.0001	0.0046	<0.0001	NS	NS	0.001	<0.001
Trellis Height × Year	NS	NS	NS	0.0014	NS	0.0073	NS	NS	NA	NA

NS=not significant at p>0.05; NA=not applicable due to 1 or no replicates

Table 5. Significance of p values for the effect of bine pruning and cultivar on average hop yield as lbs/acre at 10% dry weight for low trellis hop as determined by analysis of variance

	AlphAroma	Cascade	Newport	Perle	Summit
Pruned	NA	NS	NS	NA	NS
Cultivar	NA	NS	NS	NA	NS
Pruned × Cultivar	NA	NS	NS	NA	NS

NS=not significant at p>0.05; NA=not applicable due to 1 or no replicates

Table 6. Significance of p values for the effect of cultivar, trellis height, and hop yard on potato leaf hopper damage as determined by analysis of variance

	2015	2016	2018
Cultivar	<0.0001	<0.0001	<0.0001
Trellis height	NS	NS	NS
Hop yard	NS	<0.0001	<0.0001
Cultivar × Trellis height	NS	NS	NS
Cultivar × Hop yard	0.0038	0.0001	0.0001
Trellis height × Hop yard	0.0026	NS	NS
Cultivar × Trellis height × Hop yard	NS	NS	NS

NS=not significant at p>0.05

Table 7. Significance of p values for the effect of cultivar, trellis height, and year on downy mildew infection as determined by analysis of variance

	Lockwood Farm	Valley Laboratory
Cultivar	0.0276	0.0241
Trellis height	NS	NS
Year	NS	<0.0001
Cultivar × Trellis height	NS	NS
Cultivar × Year	NS	0.0015
Trellis height × Year	NS	<0.0001
Cultivar × Trellis height × Year	NS	NS

NS=not significant at p>0.05