The Use of Geostatistics to Analyze Factors Influencing Hop (*Humulus lupulus*) Yield in Connecticut

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Introduction:

Hops (*Humulus lupulus*) are one of the main ingredients in beer. With the growing popularity of India Pale Ale (IPA) style beers and the rapid rise of microbreweries, hop production has become a popular agricultural crop for farmers in the United States. In a relatively short time, IPAs have become the leading craft beer and the third most popular beer style in the United States (Cantwell, 2018). In 2018, the number of microbreweries in the U.S. surpassed 7,000, a new high mark, and they were expected to exceed 8,000 in 2019 (Snider, 2018). There were over 24,000 hectares of land in hop production with sales exceeding $583 million in 2018 (IHGC, 2019). While hops are primarily grown on farms in the Pacific Northwest, they have become a popular niche commodity crop on the East Coast. Research conducted in support of hop production and the introduction of precision agriculture with better understanding of how the differences in soil nutrients and weather could influence hop yield will assist growers in the Northeast.

The importance of hop production as a crop has grown rapidly throughout the Northeast. "The craft brewing industry is one of the fastest growing alcoholic beverage markets, increasing an annualized 18.8% in total revenue from 2010 to 2015" (Stemple, 2016). Stemple examined the economic impacts of hop production and the growth of the industry and concluded that this crop could be a good investment for small growers and for associated craft breweries, a study conducted by the Brewers Association found that 67% of craft beer drinkers considered whether a beer was from a local brewery prior to making a beer purchase (Watson, 2015). The resurgence of interest in local hop production led to CAES research on cultivar selection, trellis effects and the feasibility of hop farming in Connecticut (Maurer et al, 2017) and the development of integrated pest management guidelines to control pests and diseases which threaten hop yield and quality (Allan-Perkins et al., 2019).

Crop yields can vary considerably over one field. Understanding the underlying causes of this variability is key to improving and optimizing crop yield. There are two approaches for understanding factors that influence yield: (1) replicated, randomized experiments that seek to carefully control variation in the factors of interest, and (2) correlational studies, which can analyze data with respect to existing underlying variation. One form of correlational analysis is spatial or geostatistics, first used by Mercer and Hall (1911) at Rothamsted Experimental Station, in examining the variation between crop yields in small plots. They observed that plots adjacent to each other were more similar than ones farther away. This fundamental spatial statistical property was then used in a sophisticated way to predict where valuable ores would be most concentrated, in an approach called kriging (the method is named for the individual who pioneered this method). Matheron (1963), further developed the concept that neighboring samples could be used to improve prediction in a framework of regionalized variable theory (Oliver, 2010). Kriging as a method uses the relationship between position of where samples are taken and measurements from those samples to estimate the expected values for intermediate locations. These methods are useful in many fields, including precision agriculture. In traditional agriculture, samples are taken at random points of a field and mixed to form a composite sample to estimate the average nutrient values and fertilizer needs for that field. Large fields may have considerable variation present, which would be hidden when forming composite samples. Precision agriculture uses soil samples taken at set intervals, which are then analyzed via a kriging model to estimate the fertilizer needs as a response surface for the entire field. Sophisticated fertilizer application equipped with GPS (global positioning system) may then use this response surface to apply fertilizer according exactly to the predicted needs within the field, so that the grower can then achieve uniform development of plants and optimize yields. This, along with advanced harvesters equipped with GPS, allows yield to be tracked in each plot of the field. Kriging models gives farmers information that permits fine-tuning of fertilizer application.

The overall and the spatial variability of crop yields can be affected by weather conditions and field topography: for example, water will flow downhill based on the slope of the field, carrying with it solubilized fertilizers. Therefore, topographical slope influences nitrogen content of soils (Kravchenko et al., 2005). The objective of this study was to use kriging methods and spatial variability in both underlying factors that might influence yield, along with yield, to better understand the environmental and cultural production factors which significantly influenced hop yield in the two CAES hopyards.

Figure 1: This figure displays the locations of the two experimental farms that the hop data, weather and soil samples were collected from.

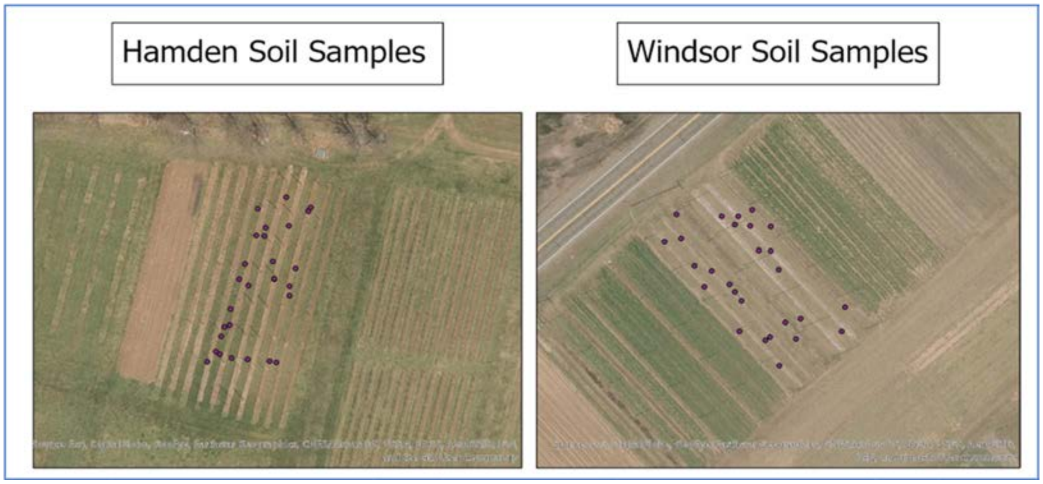

Figure 2: This figure displays the sample maps of locations sampled in each field. Samples were tested for Nitrate levels and pH. 28 samples were tested in Hamden and 27 were tested in Windsor. Originally it was supposed to be 30 for each.

Methods:

Study Area: This study included two locations, hopyards in Windsor and Hamden, located about 40 miles apart (Figure 1). Hamden is closer to the Long Island Sound, while Windsor is in the Connecticut River Valley in north central Connecticut. These two farms have different soil types. The Windsor hopyard is on a Merrimac sandy loam soil with a moderate moisture holding capacity. The Hamden hopyard is situated on a Cheshire fine sandy loam with a high moisture holding capacity. The soils during collection displayed different colors, Hamden having a darker tone. Hamden samples also were more moist. Plots in both hopyards consisted of 5 plants 3 feet apart in rows. Rows were 9 feet apart with grass that is mowed regularly – these plots are not bare soil.

Data: In agriculture, weather and soil have a huge impact on the crops grown in an area and how much fertilizer is needed. The data collected involved soil samples, weather, hop yield and quality for 2019, and GPS coordinates from specific points from which yield data were collected.

The soil was tested using the Morgan Method every spring; this gives a whole-field assessment of the soil nutrients and qualities needed for that growing season (Lunt et al. 1950). However, soil is known to vary over area, so in this study 28 samples were taken from Hamden and 27 from Windsor (Figure 2). Sample locations were determined using a random number generator in MS Excel, which corresponded to points to sample within plots in the field. The position of each sample taken was confirmed with a Garmin GPSmap 60CSx (Garmin Ltd., Olathe, KS). Soils from these samples were tested for nitrate levels and pH levels. Nitrate levels were tested using a LaMotte soil testing kit, which is a colorimetric testing method. pH was tested using a Vernier pH sensor, with a Lab Quest 2 interface, glass electrode pH meter (Lunt et al., 1950).

Data for these hops have been collected every year they have been established. Yield, moisture and hop quality is tested yearly and recorded. Yield is the primary focus of this study.

GPS coordinates of each plot were used in conjunction with map GIS (geographic information system) software. The data were taken from the GIS software and entered into MicroSoft Excel to run statistics to find any significant correlation between them. These results were then used to generate a continuous surface (Figures 3 and 4) of pH and nitrate levels across the plots using kriging ArcGIS Pro 2.4.1 (ESRI ArcGIS Pro: Release 2.4.1. Redlands, CA: Environmental Systems Research Institute).

Weather data including rainfall accumulation and temperature data were collected from on-site weather stations. Rainfall accumulation was measured in inches and the total was used in analysis up until the date of harvest. Using the equation below, temperature data is collected every 15 minutes over the course of the day. The degree day cumulative is the time spent over 50 degrees multiplied by (T-50). 15 minutes is $\frac{1}{96}$ of a day.

$$Cumulative\ Degrees = \sum_{k-1}^{96} \frac{(T-50)}{96}$$

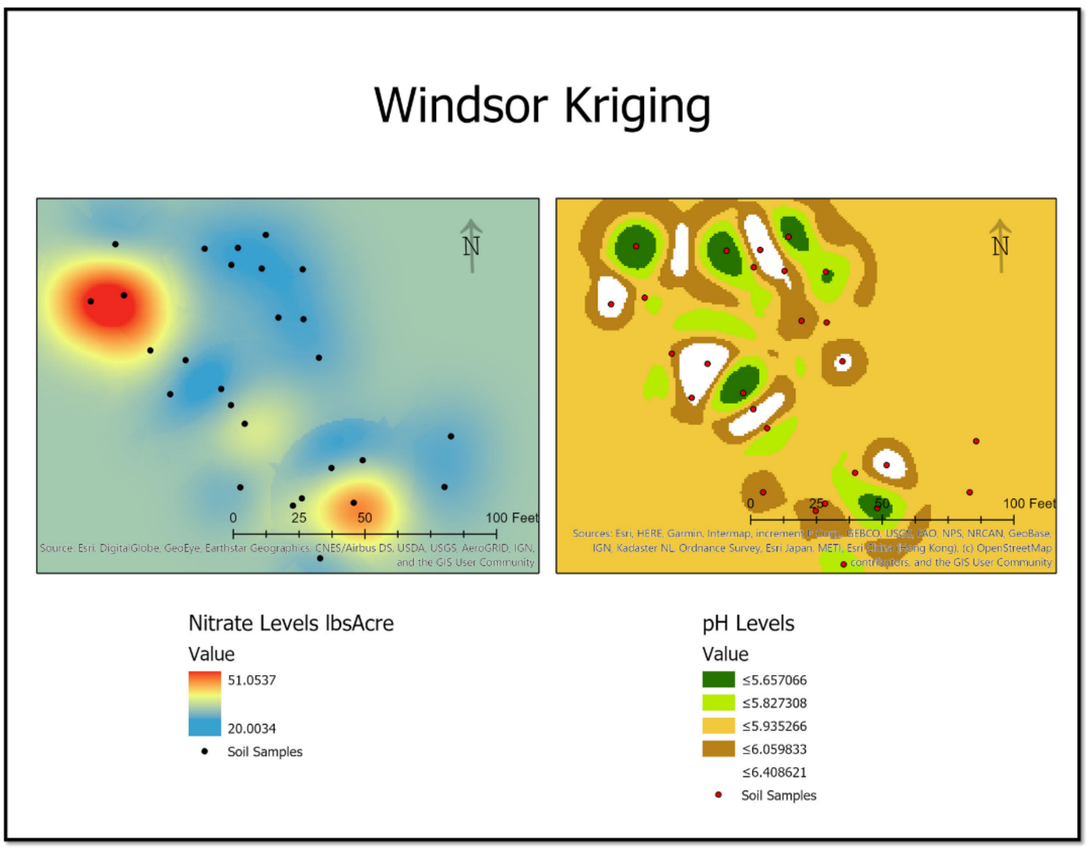

Figure 3: This displays the Kriging model generated in which the nitrates and pH for the Windsor hop yard, based on the 27 soil samples.

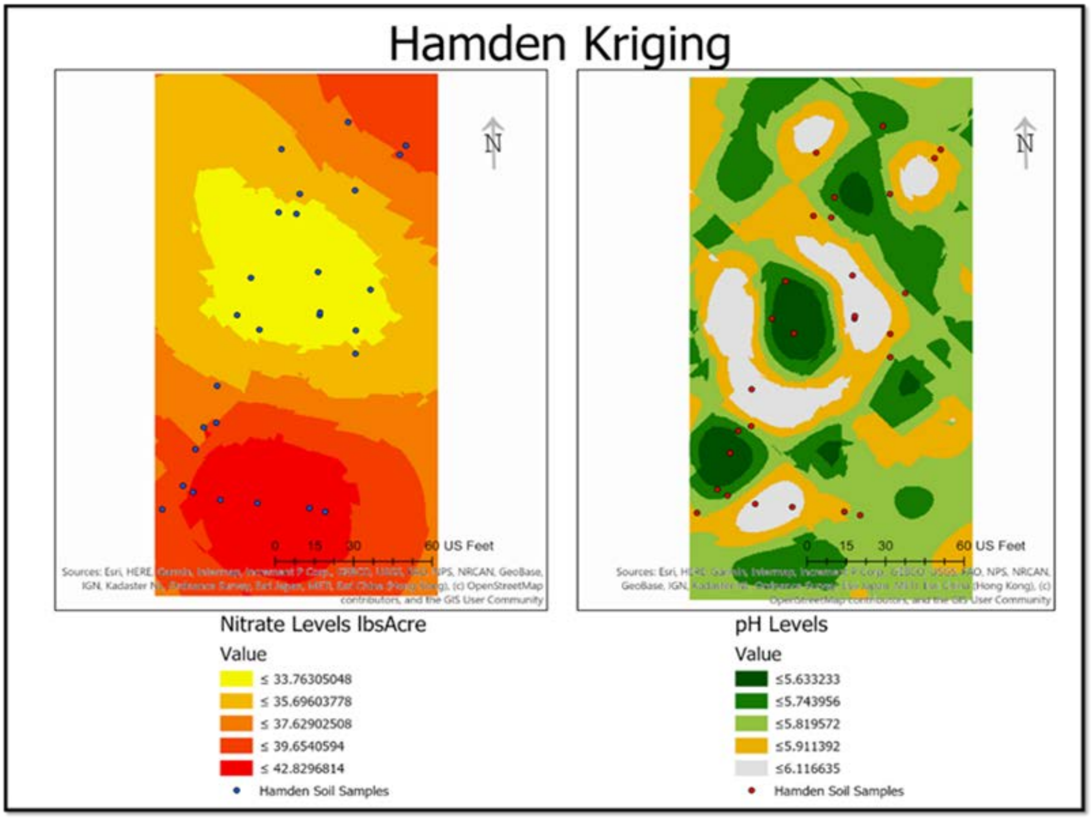

Figure 4: This figure displays the Kriging model generated in ArcGIS Pro, of the Hamden hop yard, based on the 28 soil samples.

In order to associate the hop plants and yields with the soil and site conditions, GPS points were recorded for the front and back polls of each row of hops. In ArcGIS Pro, the points of each row were generated into a line, this line was then used to generate points along it. To do this the length of the line had to be divided by the number of plants to get the proper spacing. These points were then assigned the proper plot associated with them. These were then joined with excel datasets that included yield, rainfall, temperature, Morgan Method results and the rest of the data collected.

A kriging model was constructed using the soil sampling points and joining them with the results of the soil tests to predict these nutrients across the whole field. These were run once for nitrates and pH at each location and were run using various Kriging methods to obtain the best results (Figures 3 and 4). An extract value was run to get the nitrate and pH value for each plant. This was also done with the slope, aspect and elevation for each plant. Elevation data was obtained from a Connecticut DEM (UCONN, 2016).

In order to assess which factors have a greater role in determining hop yields, three linear ordinary least square regression models were used. A combined Windsor and Hamden model and two separate Windsor and Hamden models. These regressions included the yield as the dependent variable, while the rainfall, nitrate, pH, cultivars, elevation, aspect and slope were the independent variables.

In order to incorporate the cultivars, trellis and aspect data into the models they were transformed into dummy variables. In particular, aspect values were recoded to capture the following cardinal directions: North (315 to 45), East (45 to 135), South (135 to 225), and West (225 to 315). All statistical analyses were run in SPSS version 24 (IBM Corp. Released 2016. IBM SPSS Statistics for Windows, Version 24.0. Armonk, NY: IBM Corp.).

Results:

The results from the combined regression analyses show that 11 variables explained 84.4% (Adjusted $R^2 = 0.844$) of the variation $R^2 = 0.844$in yield; separate regression analyses for Hamden and Windsor sites explained 84.4 and 93.5% of the variation in yields at those sites, respectively (Table 1). These regression statistics are interpreted as follows: for categorical variables (such as cultivars) the model coefficient predicts the deviation from the overall mean. In the case of trellis as a factor, the coefficient of -1.16 in Windsor indicates that yields from low trellis plots were, on average, 1.16 kg less than those from high trellis plots at this site, averaged over all cultivars. This loss of yield in using the low trellis varied with cultivar, though, as some cultivars did not even yield 1.16 kg per sample. For continuous variables such as nitrogen, a positive coefficient indicates that increasing levels of soil nitrogen are associated with higher yields. Overall, yield was improved at the lower parts of the field, where the ground approaching horizontal, and with a northern aspect. Yield interpretations have to be conducted within a column in the table, because overall constants used in the three regression equations (represented by the three columns in Tables 1 And 2) differ. However, Cascade was one of the best-yielding cultivars, while Alpharoma, Centennial, and Newport had low yields.

Discussion:

A number of the variables tested were significantly correlated with variations in hop yield. Cultivar, trellis system, elevation, slope, aspect and nitrogen all had significant impacts on hop yield. These results also highlight the importance of choosing an appropriate site on which to plant a hopyard, especially regarding the ability to provide supplemental irrigation.

Cultivars have been shown to respond differently to disease and the growing conditions on either coast. Cultivars on the East Coast have different alpha and beta acids that give them different flavors desired by brewers. Cascade is the most common hop cultivar on the East Coast and has been the highest yielding cultivar in Connecticut (Maurer et al., 2017). Many other cultivars show significant differences in yield, these include Newport, CTZ, Galena, Zeus, Chinook, Summit, Centennial, Alpharoma and Canada Redvine.

High trellis systems permitted growth of a longer vine and had statistically higher yields than low trellis plots. Yields from the low trellis ranged from 38 to 80% of the yield from the same cultivars grown with high trellises; cultivars always yielded more hops when grown with a high trellis. Low trellis systems were tested as existing structures for shade tobacco farmers who were interested in growing hops.

Hop plants require at least 24-28 inches of water per season (Jackson et al., 2019) Rainfall is key for any plant's development. Droughts can ruin crops of any kind and hops are no different. Hop ripeness is determined by the moisture content. In long droughts, hops can dry out prematurely and ripen too quickly. Cones will turn brown when they dry out and fall apart during harvesting, affecting yield and quality. The slope of a field can influence the flow of water and dissolved nutrients. Assuming everything moves downhill, plants at a steeper slope would be at a greater risk of losing nutrients and water. The aspect of the slope could also have an impact on the moisture of the soil based on the amount of sunlight.

A Master's thesis study (Forward 2017) in North Dakota compared the effects of mulch and nitrogen source on hop establishment and growth, concluding that mulch was a factor in weed control, and would be beneficial for hop growers, because it increases the water quantity in the soil. The hops in Windsor and Hamden have been mulched to benefit them, primarily for weed control.

The aspect, the direction in which the slope faces, will also determine the amount of sunlight. A steep southern aspect would receive the most sunlight during the day in the northern hemisphere, but also could lead to greater drying of soil. Hops in this experiment appeared to benefit from not having a southern aspect to slope. In Hamden, having an aspect to the east also was correlated with improved yield. This was not consistent between sites. However, as the Windsor site is nearly horizontal, a lack of significant influence of aspect at Windsor should have been anticipated. In both the individual regressions the trellis system, cultivar, elevation and slope were consistent for influencing the yield of the hops, with cultivar and trellis height being the largest contribution to experimental variation in yield.

Conclusion:

This exploratory study successfully used geostatistics to examine several variables that may influence hop yields in the Northeast. As a correlational study, these data are best used to determine which factors need to be studied further through controlled experiments to maximize hop yields. In conclusion, the environmental impacts on hops varies based on location. When combined, the data shows multiple variables significantly affected hop yields, including cultivar, trellis height, slope, and nitrate level in soil. Variations in soil pH, initially anticipated to affect yield, was not significant. Different environmental variables were correlated with yield at the two locations. These inconsistencies could be due to unique characteristics for each site (e.g., a nearly level, horizontal field in Windsor vs. a sloping site in Hamden).

Future research should include testing the soil for other nutrients like calcium, phosphorus, sulfur, and other nutrients. These could be having a larger impact on the yield than the pH or nitrate levels. Additional years of testing of cultivars, collecting yield data and soil sampling each plot would provide a more in-depth look at the variation across the field.

Table 1. Regression results for hops grown in Windsor and Hamden. The values given are the significant ($P < 0.05$) regression coefficients for the effects on yield.

Variable	**Hamden**	**Windsor**	**Combined**
Trellis height			
Low	-1.104	-1.159	-0.984
Nitrate	0.067	0.023	0.019
Elevation	-0.104	-1.406	-0.039
Slope	-0.213	-0.35	-0.026
Aspect south	n.s.	n.s.	-0.631
Aspect west	-0.469	n.s.	n.s.
Cultivar			
Alpharoma	1.326	n.s.	-2.59
Canada Redvine	2.92	n.a.	-0.865
Cascade	1.843	0.964	0.536
Centennial	n.s.	-3.719	-3.213
Chinook	0.826	-0.606	-0.629
CTZ	2.176	n.a.	n.a.
Galena	2.845	-0.943	-0.801
Newport	n.s.	-3.124	-2.371
Summit	2.127	-2.219	-1.933
Zeus	n.a.	-0.76	n.a.

n.a., not applicable; n.s., not significantly different from zero

Table 2. Hop Yield in Hamden and Windsor hopyards (pounds per plot).

Hop Cultivar	**Hamden**		**Windsor**	
	Low trellis Mean sd (n)	**High trellis Mean sd (n)**	**Low trellis Mean sd (n)**	**High trellis Mean sd (n)**
Alpharoma	0.9 0.1 (4)	2.2 0.6 (4)	nd	nd
Cascade	4.3 0.4 (4)	6.1 2.4 (5)	9.4 2.3 (4)	11.8 1.1 (5)
Galena	3.5 0.2 (2)	7.2 - (1)	nd	nd
Newport	1.1 0.4 (5)	1.8 0.4 (5)	1.0 0.3 (4)	2.0 0.4 (4)
Summit	nd	nd	2.2 0.7 (4)	5.7 - (1)

\- = cannot be computed
nd = no data available

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