Validating a Prescription Map used in Variable Rate Irrigation using Geographic Information Science

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Abstract

Prescription maps are available commercially and widely used in center pivot irrigation systems for the purpose of applying variable rates of water in specified zones of a field. The objective of this study was to determine if the prescription map used for a center pivot irrigation system delivered adequate water content in a corn field in Belgrade, MN USA. To understand field variability in this study, apparent Electrical Conductivity (ECa), Topographic Wetness Index (TWI), and Available Water Storage (AWS) were used to guide sampling strategies for the purpose of measuring soil moisture with a neutron moisture meter (NMM). The prescription map was found to be valid in 7 out of 11 locations tested, or 63%, using high yield as a successful outcome.

Introduction

Around 70% of the fresh water sources in the world are used in agriculture for irrigation (WWAP, 2015). Irrigation changes the natural process of the water cycle because it can be pumped from the ground or from surface waters (Irrigation Water Use, 2015).

Irrigation water use is affected by irrigation management decisions in agriculture production. Irrigation allows crops to grow when precipitation is not timely or available. The objective of irrigation management is to regulate the amount of water in the soil to optimize the growing conditions of crops so the soil has the right amount of water, at the right moment in time and space. The amount of water in the soil is affected by weather variability, soil properties and soil texture, plant biology, and topographic features. This variability complicates the process of measuring and modeling water, soil, and plant response (Corwin, 2008). Thus, growers make considerations in irrigation management based on how much water is needed, where it is needed, and when it is needed during the crop's growth cycle (Evett, 2007).

One efficient and popular system used in irrigation management is a center pivot system. Center pivot infrastructure consists of steel pipe spans supported by towers with wheels. The center pivot starts at a central location in a field and stretches outward along a line and rotates in a circle. Traditionally, the outer end of the center pivot moved faster than the spans closer to the pivot point. Valves and nozzles on each pivot span are sized to match the increase in speed as they moved further away from the pivot point (Evans, LaRue, Stone, and King, 2013).

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In recent years, growers have optimized crop performance by distributing water to specific locations. This has been validated by placing water cylinders at random locations in the field (Hedley and Yule, 2009). The most common types of site-specific irrigation for center pivots are sector and zone control (Evans *et al*., 2013).

Sector control is dependent on speed of travel. More water can be applied by slowing the pivot speed down and less water can be applied by speeding the system up. These sectors are similar to pieces of a pie, and the size of each sector depends on the manufacturer, but can be anywhere from 1 to 10 degrees. Thus, water can be controlled in 36 to 360 sectors in the field. Costs to adopt sector control are very low since it relies on control technology that is inherent to historical pivot design (Evans *et al*., 2013).

Zone control, on the other hand, is subdivided into sections which lie between the wheels of each pivot span. These sub sections are known as zones. Zones can be as narrow as single nozzle spacing or can represent a group of nozzles on a pivot span. The amount of water in every zone can be changed based on the variability in a field. The cost of zone control is substantially greater than sector control as it demands additional equipment and technology. Adding zone control to a pivot can cost $20,000-$40,000 USD (Evans *et al*., 2013). Included in those costs are installation of the system, valves, nozzles, and the software and hardware designed to run the system. Running these systems can help growers meet the water demands of their crops without degrading the environment, as water is used more efficiently. This prevents nitrates from leeching and aquifers are continually replenished (Power, Wiese, and Flowerday, 2001).

Zone control allows the variability of soil and other factors to be characterized in the form of a map, widely known as a prescription map. The central control panel on the pivot has the capability to upload prescription maps which contain the information on how much water to apply in each zone. The process of distributing variable rates of water in each unique zone in the field is known as site-specific variable rate irrigation (SS-VRI) (O'Shaughnessy, Evett, Colaizzi, and Howell, 2012).

Many studies have advanced research on SS-VRI, such as understanding and relating apparent electrical conductivity to soil properties, delineating fields into site-specific management zones for improved water use, and even soil moisture monitoring networks which derive daily maps for upload to the irrigation system. The products farmers purchase in the marketplace are often not of the same quality. One problem is that prescription maps are static and disregard the spatiotemporal variability of crop water stress throughout the growing season (O'Shaughnessy *et al*., 2012).

SS-VRI has been offered by irrigation manufacturers for the last couple of decades although adoption of the technology is still limited due to factors such as inexpensive water cost, regulation, competing patents, liability, and proprietary software. Valmont Industries Inc, began offering the zone control packages in 2010 (Evans *et al*., 2013). Evans *et al*. (2013) also found in 2012 only about 50 center pivots out of 175,000 were using zone control in the United States.

Even though SS-VRI using zone control was unavailable five years ago, it is likely more growers will begin to adopt the technology due to recent events. The

Minnesota DNR has begun implementing a pilot ground water management program in the Bonanza Valley (Bonanza Valley Groundwater Management Area Plan, 2014), one of Minnesota's most heavily irrigated areas authorized by the legislature of Minnesota under statute 2015, section 103G.

Much of this area has sandy soil, so when farmers apply fertilizers to their fields it is easier for nitrates to leech into groundwater aquifers because they percolate faster than other soils (Dylla, DeMartelaere, and Sutton, 1975). Additionally, site-specific irrigation management is seldom the focus of conservation water plans even though several studies show significant efficiencies in water use (Evans *et al*., 2013). Evans *et al*. (2013) suggests conservation plans should provide documents which explain best management practices for site-specific variable rate irrigation (SS-VRI).

One proven and tested way to characterize soil texture variability is with apparent Electrical Conductivity (ECa). ECa has the capability to measure the relative texture in the soil through a device that emits an electrical current and stores the reading which can be referenced to a point in the field. The electrical current penetrates around 5 feet into the ground which provides a relative texture value for the root zone. The locations can be geolocated and interpolated to provide a soil texture map (Corwin, 2008).

One way to validate if water is sufficient during the growing season is to measure the water content in the soil. There are many devices which measure soil moisture, but the most accurate is a Neutron Moisture Meter (NMM). The Neutron Moisture Meter emits epithermal neutrons from a probe located inside the meter. These neutrons interact with hydrogen atoms present in water. Hydrogen atoms slow the neutrons through a process of thermalisation. These thermalized neutrons can then be detected by the probe and counted by the meter. The meter then computes the counted neutrons into a measurement of volumetric water content (Evett, 2007). The NMM measures, at minimum, a volume of ½ cubic foot. The number of devices needed to measure water content across the field is contingent upon the type of device used to measure water content and the information about the soil and plant environment (Dane, Topp, Campbell, Horton, Jury, Nielsen, and Topp, 2002). Since a NMM can measure such a large area compared to other soil moisture devices, fewer sampling locations are needed (Evett, 2007).

Although the device is highly precise and accurate, more accurate estimates can be taken with the addition of a depth control stand. The moisture readings are more accurate at the 6-inch level, and the stand keeps the moisture meter at a constant level above the ground and is not affected by settling soil (Evett, Tolk, and Howell, 2003).

Prescription maps have been widely used in site-specific management in agriculture. A few studies in Minnesota have used apparent Electrical Conductivity in order to explain soil texture, but none have been used for the purpose of guiding field sampling strategy for the placement of neutron probes to validate prescription maps (O'Shaughnessy *et al*., 2012). This research provides validation for a prescription map which gives growers a good understanding of how well it performs when the map is derived from John Deere RTK elevation (assuming higher elevations hold less water than lower elevations). The objective of this research was to validate a prescription map and understand where the study site had too much water and where it was lacking water.

Study Area

A 120-acre corn field located at 45°27'32.2"N, 95°02'03.1"W was chosen for the study because it is one of the first zone SS-VRI systems in the heavily irrigated Bonanza valley, and the Bonanza Valley is also part of a ground water management pilot program that focuses on conserving groundwater resources. The site was also chosen due to the interest of the grower in the project and his willingness to collaborate. Figure 1 shows the study site.

The study area topography ranges from 1% to 12 % slopes. The field has several hills with lighter soil on top and darker heavier soils in lower lying areas, as well as a lot of rocks near the surface. The drought-prone soils of the Bonanza valley have been extensively described (Dylla *et al*., 1975). The grower's typical practices of chisel plow tillage and a crop rotation of edible beans, corn, and sugar beets are typical of the area, with the study year's crop of corn on 22-inch rows. The center pivot area encompasses 126.54 acres, but only 112.92 acres are crop land. Timely precipitation in the amount of 22 inches fell from May 1, 2015 to September 30, 2015. The grower only irrigated the study area twice - on July 12, 2015 (1 inch) and on August 2, 2015 (.8 inches). The field exhibits variable soil types, such as Estherville sandy loam, Regal and Osakis loam, and others (Figure 2). The corn was planted and the ECa data was collected on April 14, 2015. The holes for the NMM access tubes were bored on the June 11, 2015.

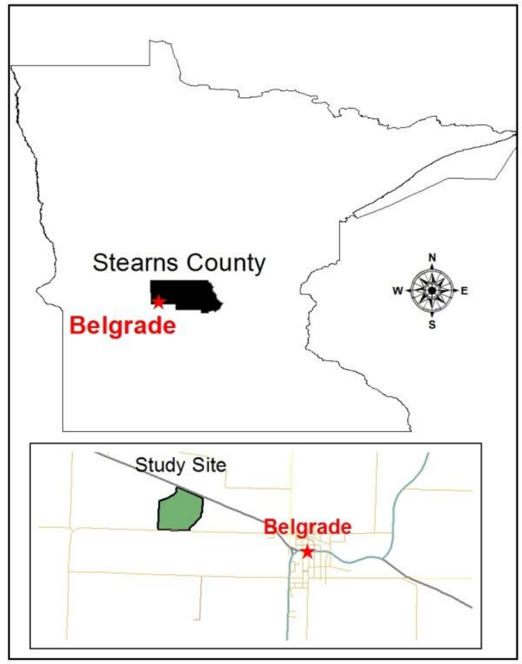

Figure 1. The corn field for study is northwest of Belgrade in Stearns County, Minnesota.

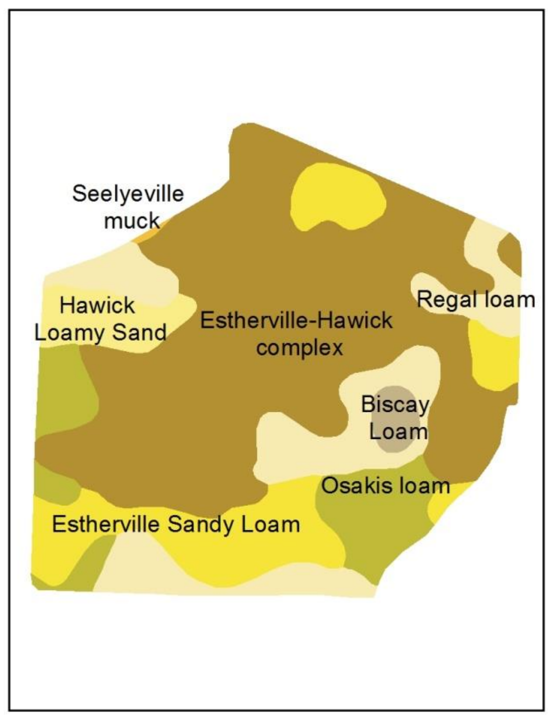

Figure 2. The Soil Survey Geographic Database (SSURGO) classified the field into 8 different soil types.

Methodology

Data Collection Process

All of the data for this project were downloaded, analyzed, and clipped to the study area using ESRI's ArcMap and ArcCatalog version 10.2.2 and stored in a geodatabase. The geographic coordinate system and projection chosen for this project was North American Datum 1983 Universal Transverse Mercator Zone 15 North. A Microsoft Access database was normalized and built to store weekly readings collected with the NMM over the course of the growing season.
Physical data collection included ECa, precipitation, and soil moisture information from the Neutron Moisture Meter. Each layer of information had a different purpose which helped to describe the variability in the study area.

The instrument used to collect and measure ECa was an EM38 manufactured by Geoincs Inc. The device sends electrical current 5 feet into the soil profile and records the measurements (Davis, Kitchen, Sudduth, and Drummond, 1997). Conductivity is an electrical current's ability to move through elements in space. ECa uses a system of two coils which log the primary and secondary currents sent from the coils based on the strength of a magnet. The relationship between primary and secondary currents is how ECa is measured (Davis *et al*., 1997). The EM 38 was secured in an enclosed box behind a tractor (Figure 3) and pulled in 50-foot sections in a north/south orientation. The measurements were georeferenced with an Archer GPS using FarmWorks software. The data points were collected every 2 seconds at an average speed of 7.8 miles per hour. The data points were ordinary kriged and interpolated in ArcGIS using the log transformation type. Log was chosen because the distribution of the ECa data was positively skewed in the semivariogram (Corwin and Lesch, 2005).

Figure 3. EM38 being calibrated (top left). After calibration, it is placed in the black box and pulled with a tractor across the field to record ECa data.

Three layers were chosen to characterize water content across the study site due to each layer's unique characteristics and the ease of access to the information. Those were the soil's ability to store water (AWS), the texture which allows water to percolate (ECa), and areas where water pools (TWI).

A 1-meter Digital Elevation Model was downloaded from the Minnesota Geospatial commons website. The raster was processed with a Topographic Wetness Index tool which calculates the natural logarithm of area divided by the slope. The output produced a raster which shows where water pools (Jenness, 2006).

Soil types and their respective available water storage (AWS) in the 3-foot profile were extracted from the Soil Survey Geographic Database (SSURGO) through a series of reclassifications with the raster layer (Soil Survey Staff, 2013).

A stratified random sample was chosen to guide the sampling strategy for the placement of NMM access tubes. The sampling strategy characterizes some field variability by delineating the study area into zones, also known as strata (Corwin and Lesch, 2005). In order to process the sampling layers and preserve each layer's cell values ranging from low to high (Figure 4), the raster layers were reclassified as follows: 2 strata for AWS values (1 & 2), 3 strata ECa values (10, 20, & 30), and 4 strata TWI values (100, 200, 300, 400). The map algebra tool was utilized which stacks each layer on top of another and adds the cell value of each cell in each layer. For example, a stratum with a classification of a 132 had low TWI (1), a high ECa (3), and a high AWS (2).

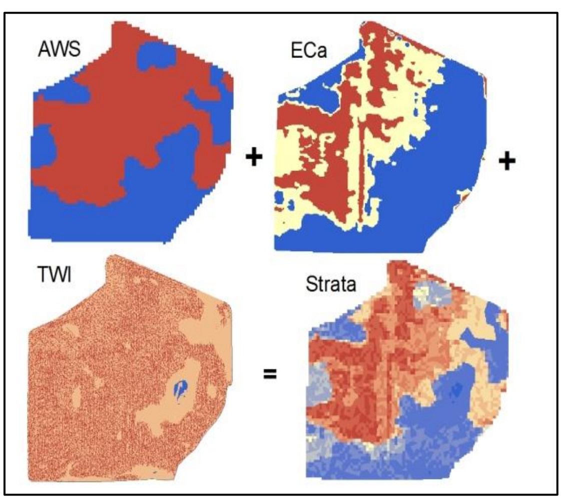

Figure 4. Red indicates areas with less soil water holding capacity. Blue indicates more soil water-holding capacity.

Figure 5 displays the study area delineated into 13 strata. Figure 6 shows where the tool selected one location in each unique stratum (Buja and Menza, 2013).

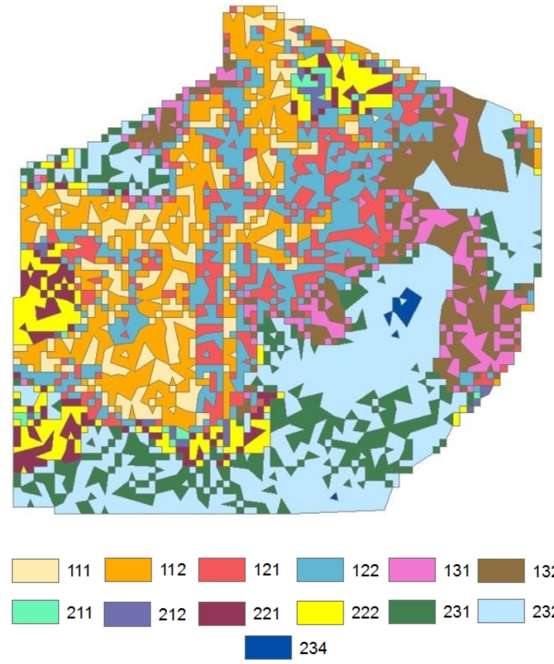

Figure 5. Study area delineated into unique strata, with legend showing the number classification after running Map Algebra.

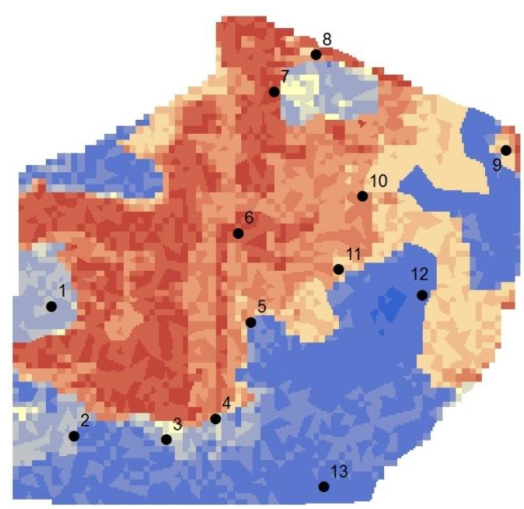

Figure 6. Map showing tube locations randomly selected within each strata.

Holes were then bored into the ground with a probe truck using a 3-inch diameter auger (Figure 7). The NMM access tubes were installed and backfilled while preserving the soil texture as much as possible. A rain gauge was used to collect precipitation information.

Figure 7. National Resource Conservation Service boring the sample location holes with an auger on the probe truck.

Next, a depth control stand was built which controls the readings relative to the soil surface (Evett *et al*., 2003).

Weekly readings throughout the growing season were taken at each tube at 6-inch intervals down to 36 inches in the root zone (Figure 8). A normalized database was built to store the soil moisture information from the NMM (Figure 9). The prescription map (Figure 10) was manually acquired from the grower. He used a John Deere RTK elevation map to delineate the field into zones using a proprietary software package from Valmont Industries Inc.

Figure 8. Collecting data using the NMM, the depth control stand, and the rain guage.

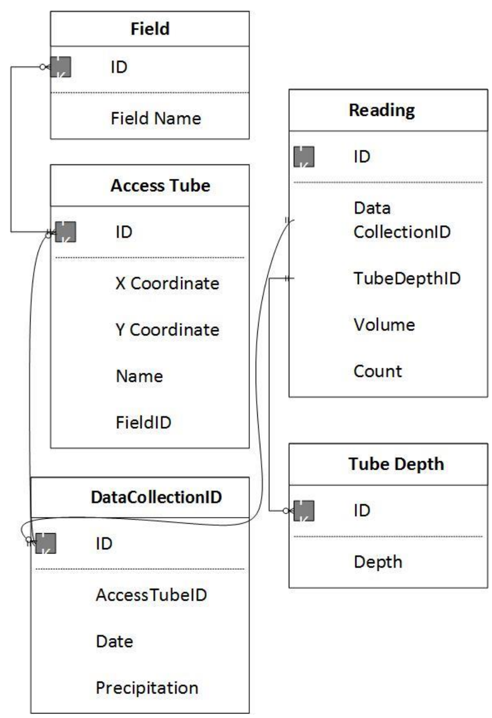

Figure 9. Entity Relationship Diagram of the NMM information.

The field had 5 meters of elevation change from the top to the bottom. Each meter was delineated into a zone so the higher elevations received 100% irrigation use, while the lower elevation received 50%. Each zone was assigned manually by the grower. It was assumed higher elevations had less water holding capacity and the lower elevations had more water holding capacity.

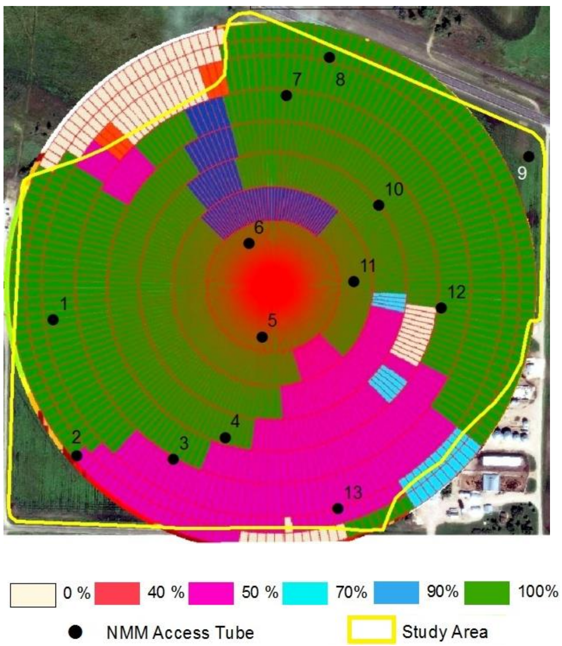

Figure 10. The grower's prescription map and tube locations indicated with black dots. The yellow outline is the boundary of the corn field.

Towards the end of the growing season, the grower decided to harvest a portion of the field for silage. Thus, a known area around each access tube was hand harvested and yield adjusted to 15.5% moisture for yield information. The rest of the field was cut with a John Deere combine with an on-board yield monitor. The portions of the field cut by the combine were averaged and compared with the hand-harvest yield data.

Data Preparation

A Microsoft Access database was built to store the NMM soil moisture information. Several queries were used to extract soil moisture information by depth, tube, and date for further statistical analysis. A file geodatabase was used to store all feature class layers such as soil type from SSURGO, ECa, NMM access tube locations, yield, and raster files derived from a 1-meter DEM.

Spatial Analysis

The prescription mapping software used by the grower had no spatial components or tools available to project the map into a Geographic Coordinate System (GCS). As a result, the image of the prescription map was georeferenced using an aerial image from Digital Globe (2014) as an overlay in ArcGIS. Once the image was rectified it was exported as a raster and projected. Each NMM access tube location was added to the display to verify the zone of each tube in the prescription map. NMM access tubes 1, 4, 5, 6, 7, 8, 10, 11, and 12 received 100 % irrigation. Tubes 2, 3, and 13 received 50%. Tube #9, 0%, was outside the pivot and was therefore excluded from the study.

Statistical Analysis

The first step in the statistical analysis was to explore the data in SPSS. The NMM soil moisture data was analyzed for normality. Leven's test was run to test the hypothesis of equal variances.

Polynomial linear regression was used in MS Excel to determine the relationship between yield and NMM soil moisture data using the polynomial linear regression equation and r squared value.

Results and Discussion

Three-Factor ANOVA

The soil moisture readings from the NMM meter were chosen as the dependent variable to test if the data were normally distributed across depth, NMM access tube location, and date. Here, differences were found between all three which were highly significant (P<.0001). Histograms, normal Q-Q plots, and whisker box plots revealed the NMM soil moisture data were not normally distributed.

A non-parametric Leven's test was used. Some steps were taken to create new variables in order to test the null hypothesis to assume equal variances with non-parametric data. The null hypothesis was rejected (P <.05) and it was concluded equal variances could not be assumed. Further statistical analysis would be needed to test if unequal variances could be assumed to run the 3 factor ANOVA without replication in order to have reliable results.

2nd Order Polynomial Regression

The hand harvested yield information was used as the dependent variable. The mean values of each NMM access tube were used as the exploratory variable. NMM access tube #8 was removed because it was an outlier in terms of yield, soil texture, and mean soil moisture. At the time of soil sampling, the area exhibited unusual soil characteristics to the Estherville soil series commonly found in the Bonanza valley. The mean soil moisture values at this location were above 20 percent throughout the profile (0-36 inches) during the growing season, indicating optimal growing conditions in this area but unrepresentative of the field as a whole. Lastly, the polynomial linear regression equation was improved by .16 which significantly improved the model.

The linear regression equation for Figure 11 was $y = -1.4307\ x^2 + 47885x - 133.71$. The R^2 was value was .5979. The soil moisture information was positively and significantly correlated with the yield criterion (P<.0001). Figure 11 shows the linear regression curve. Low soil moisture and low yield was expected and is revealed at locations 7 and 9. High soil moisture also had low yield at locations 11 and 13.

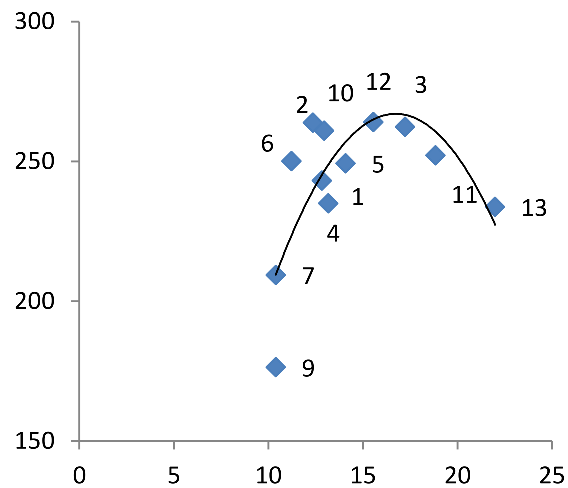

Figure 11. Linear regression curve for soil moisture (X axis) and yield in bushels per acre (Y axis).

The NMM access tubes which performed optimally were between 12 and 16 percent soil moisture. This included tubes 1, 2, 3, 4, 5, 6, 10, and 12. Those below and above this range were 7, 11 and 13 (Figure 12).

Since 13 NMM access tubes represented 13 unique zones it is evident that zones 112, 131, and 232 - representing 7, 11, and 13 respectively - need either more or less water (Figure 13). NMM access tube 2 performed well in the model even though it was only in the 50% irrigation rate (IR) group which indicates it may perform even better with a higher IR, but this would need to be verified with the help of soil texture analysis. Access tube 7 had low soil moisture and was in the 100% irrigation rate indicating even with full irrigation it may need more water in a more timely fashion.

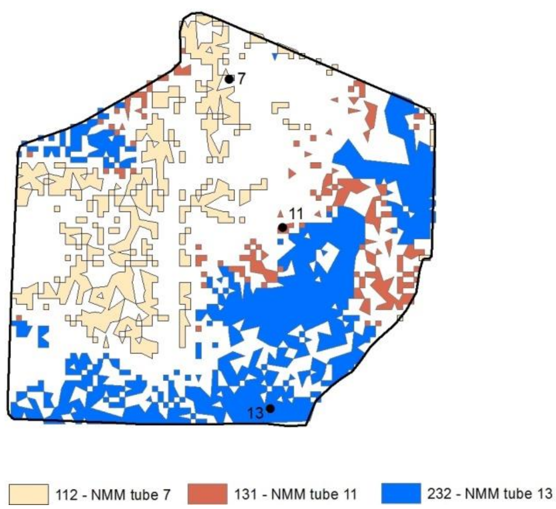

Figure 12. Strata with low yield due to high or low soil moisture.

NMM Acces Tube	7	11	13
Strata Classification	112	131	232
Description	Low AWS, Low ECa, Slight Slope (TWI)	Low AWS, High ECa, High Slope, (TWI)	High AWS, High ECa, Slight Slope (TWI)
Acres	16.37	5.51	29.16

Figure 13. Description of zones with low yield.

When soil samples were taken, it was observed this location had only 8 inches of Estherville-Hawick soil before the profile changed to gravelly coarse sand. This indicates the area could use more timely irrigation. The regression curve (Figure 11) started to slump at NMM access tube location 11 with a mean soil moisture of 18.84 in the 100% IR. This shows too much water was available in this area and yield began to diminish. Lastly, location 13 had the highest mean soil moisture profile at 22 percent in the 50% IR and continued to slump with a yield of 233.7 bushels per acre. A few times, location 13 had standing water in the access tube below 24 inches. This was probably the result of the depth to the water table. Also, during one day of data collection when the pivot was on, water was running downhill between the corn rows indicating saturated conditions. This indicates areas uphill of location 13 were also receiving too much water. Overall, this portion of the study area would benefit from less water in a growing season with similar weather patterns.

Lastly, the soil moisture had lots of variability by depth. A graph in Appendix A, plots soil moisture by depth and reveals the 12 inch depth to have the highest mean soil moisture while successive depths continued to drop. At the 24 inch depth a large gap exists between tubes 3, 11 and 13 and the rest. This indicates these areas have either saturated conditions or have a deeper soil profile.

Conclusions

When soil moisture is low, so is yield. As soil moisture rises, so does yield until a point where yield decreases as soil moisture becomes excessive. This suggests areas with low mean soil moisture in the soil profile perform poorly compared to other parts of the field. Areas with too much water also perform poorly. If the soil remains sufficiently water logged for an extended period of time, denitrification of soil nitrate may occur, further decreasing crop yield (Buford and Bremner, 1975).

In summary, the prescription map was valid at 7 of 11 locations or 63 % of the time. Zones with the characteristics of NMM access tubes 7, 11, and 13; represent 51.05 acres of the field which means yield could be improved in 45% of the study area by improving the water conditions in these zones. This analysis also suggests the prescription map could perform better by changing the prescription at location 2. Additional research, such as soil texture analysis, is needed in order to explain how much more or how much less water to apply in these areas.

Limitations

The Estherville soil series were characterized as uniform but there can be variances in the soil. For instance, tube 7 had 11.22 percent soil moisture but 8 had double the mean soil moisture at 21.4 percent.

Soil samples were taken later in the project and had not yet been analyzed for textural analysis at the time of this writing so the readings were not calibrated due to the timeline of the project. These variables would provide more evidence as to what might be affecting the soil moisture and yield, which could lead to better prescriptions.

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Appendix A. Variability in soil moisture by depth by tube.