Managing Variable-Rate Irrigation Using NDVI

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Abstract. *Variable rate irrigation (VRI) systems are capable of spatially allocating limited water resources while potentially increasing profits and conserving water. However, compared to traditional irrigation systems, VRI systems require a higher level of management. Delineation of management zones for spatial irrigation applications typically have been static through the growing season and has been based on grower's their past experience and knowledge of variability in their fields (soil types or soil EC). In this research, we investigated the use of static management zones and the potential use of dynamic management zones based on remotely sensed crop vegetative indices. The static zones were managed using soil properties and using an expert system. The dynamic zones were managed by using remotely sensing crop vegetative indices using Crop Circle NDVI sensors to calculate spatial crop coefficients. Initial results indicate that the vegetative indices varied throughout the field and could be used to spatially allocate water differentially.*

Introduction

Variable-rate irrigation (VRI) systems are irrigation systems that are capable of applying different water depths both in the direction of travel and along the length of the irrigation system. Spatial water applications attempt to overcome site-specific problems that include spatial variability in topography, soil type, and soil water availability. Irrigation management in some areas of the southeastern U.S. could benefit VRI because of the highly variable soils with low water holding capacities.

A widely used method of estimating irrigation requirements is the FAO-56 method (Allen et al., 1998), in which crop coefficients are used for determining the irrigation requirement of a crop over the growing season using reference evapotranspiration (ET_o) measurements. The FAO-56 method provides standard generalized estimates of the crop coefficients that may not be appropriate for every location, and it does not readily lend itself to VRI management. A potential method to estimate spatial crop coefficients than can be used in VRI systems is using remotely sensed canopy reflectance. Bausch and Neale (1987) proposed a concept for deriving crop coefficients from reflected canopy radiation. They plotted the seasonal normalized difference vegetation index (NDVI) and found that it resembled the seasonal basal crop coefficient curve. They reported that crop coefficients derived from NDVI were independent of time-based parameters such as planting date and effective cover date that are usually associated with traditional crop coefficients and that basal spectral crop coefficients were a real-time crop coefficient that permitted the crop to express its response to weather, management practices, and stresses. In a summary of vegetation index-based remote sensing for estimating crop coefficients, Glenn et al. (2011) reported that remotely sensed NDVI-based crop coefficients can help reduce agricultural water use by matching irrigation rates to the actual water needs of a crop as it grows instead of to a modeled crop growing under optimal conditions. These NDVI-based crop coefficients could also be used as a method of estimating spatial crop coefficients for scheduling spatial irrigation using a VRI system.

In this research, our objective was to evaluate and compare three irrigation management methods for their potential in managing VRI systems. The three irrigation management methods were (1) using remotely sensed crop vegetative indices to estimate crop coefficients, (2) using the Irrigator Pro for Corn expert system, and (3) using measured soil water potentials.

Materials and Methods

From 2012 to 2014, corn (*Zea mays*) was grown under conservation tillage on a 6 ha site under a VRI system near Florence, South Carolina. The soils (figure 1) under the center-pivot irrigation system are highly variable. Three irrigation treatments were evaluated for their potential utilization for spatial irrigation management using the VRI system. The first treatment was based on remotely sensing the crop normalized difference vegetative index (NDVI treatment) combined with a 7-day water balance, and irrigations were initiated when the SWP fell below -30 kPa. The NDVI treatment was used to estimate crop coefficients using methods similar to those used by Bausch (1993), Hunsaker et al. (2003), and Glenn et al. (2011). These estimated crop coefficients were used in the FAO 56 dual crop coefficient method for estimating crop evapotranspiration (ET_c) and irrigation requirements. Initially in 2012, the crop coefficients were based on the FAO 56 crop coefficients for field corn ($K_{cb\ ini}$ = 0.15, $K_{cb\ mid}$ = 1.15, and $K_{cb\ end}$ = 0.5). After crop establishment and NDVI measurements were collected, the crop coefficients were updated and estimated by multiplying the NDVI measurement by a slope of 1.5. The second irrigation treatment was based on the Irrigator Pro for Corn expert system that was developed by the USDA-ARS National Peanut Research Laboratory (Davidson et al., 1998; Lamb et al., 2004, 2007). In this research, Irrigator Pro for Corn was implemented using spatial management zones corresponding to variable soil types. Irrigator Pro uses soil texture and soil water potential (SWP) measurements to estimate the soil water holding capacity in the root zone for water balance calculations. The third and more traditional irrigation treatment (SWP treatment) was based on using SWP sensors to maintain SWP values above -30 kPa (approx. 50% depletion of available water) in the top 30 cm of soils.

The irrigation system was a 137 m center-pivot irrigation system modified to permit variable application depths to individual areas 9.1 × 9.1 m in size (Omary et al., 1997; Camp et al., 1998). The center-pivot length was divided into 13 segments, each 9.1 m in length. For this experiment, the outer nine segments (segments 5 to 13) of each pivot quadrant were used for the three irrigation treatments in a randomized block design with three replicates per quadrant (with a total of 12 replicates for the entire pivot). A more detailed description of the water delivery system may be found in Omary et al. (1997) and for the control system in Camp et al. (1998).

Crop Management: No-til corn was planted in 76 cm rows in a circular pattern with a planting population of 79,000 seeds ha^{-1}. All nitrogen fertilizer, except preplant granular applications (25 kg ha^{-1} N), was applied via fertigation. Nitrogen (225 kg ha^{-1}) was applied through the pivot via fertigation in 2012 on 25 May (90 kg ha^{-1}), 31 May and 4 June (67 kg ha^{-1}). In 2014, fertigation applications were on 19 May (90 kg ha^{-1}), 4 June and 9 June (67 kg ha^{-1}). In 2013, fertigation applications were applied on 25 May (90 kg ha^{-1}) and 17 June (67 kg ha^{-1}). The total N applied via fertigation in 2013 was reduced to approximately 157 kg ha^{-1} due to pumping plant repairs and a management oversight.

NDVI and SWP Measurements: The NDVI measurements were collected over center rows for each pivot segment throughout the growing season at approximately two-week intervals until tasseling using a Crop Circle ACS-430 active crop canopy sensor and GeoSCOUT GLS-400 datalogger (Holland Scientific, Inc., Lincoln, Neb.). The mean NDVI values were calculated from the collected reflectance measurements and crop coefficients were calculated by multiplying by a slope of 1.5. In 2012, mean calculated crop coefficients were 0.41 (2 May), 1.01 (15 May), 1.08 (24 May), 1.19 (1 June), and 1.16 (8 June, post-tassel). For 2013, mean crop coefficients were 0.38 (14 May) and 1.03 (31 May). Due to a malfunction of the GPS, no additional NDVI readings were available in 2013; therefore, the FAO K_{cb} value of 1.15 was used. In 2014, mean crop coefficients were 0.30 (6 May), 0.42 (14 May), 0.92 (27 May), 1.07 (4 June), and 1.16 (12 June). Since we did not collect NDVI readings after tasseling, the last calculated crop coefficient was the midpoint crop coefficient ($K_{cb\ mid}$) until the late-season stage ($K_{cb\ end}$).

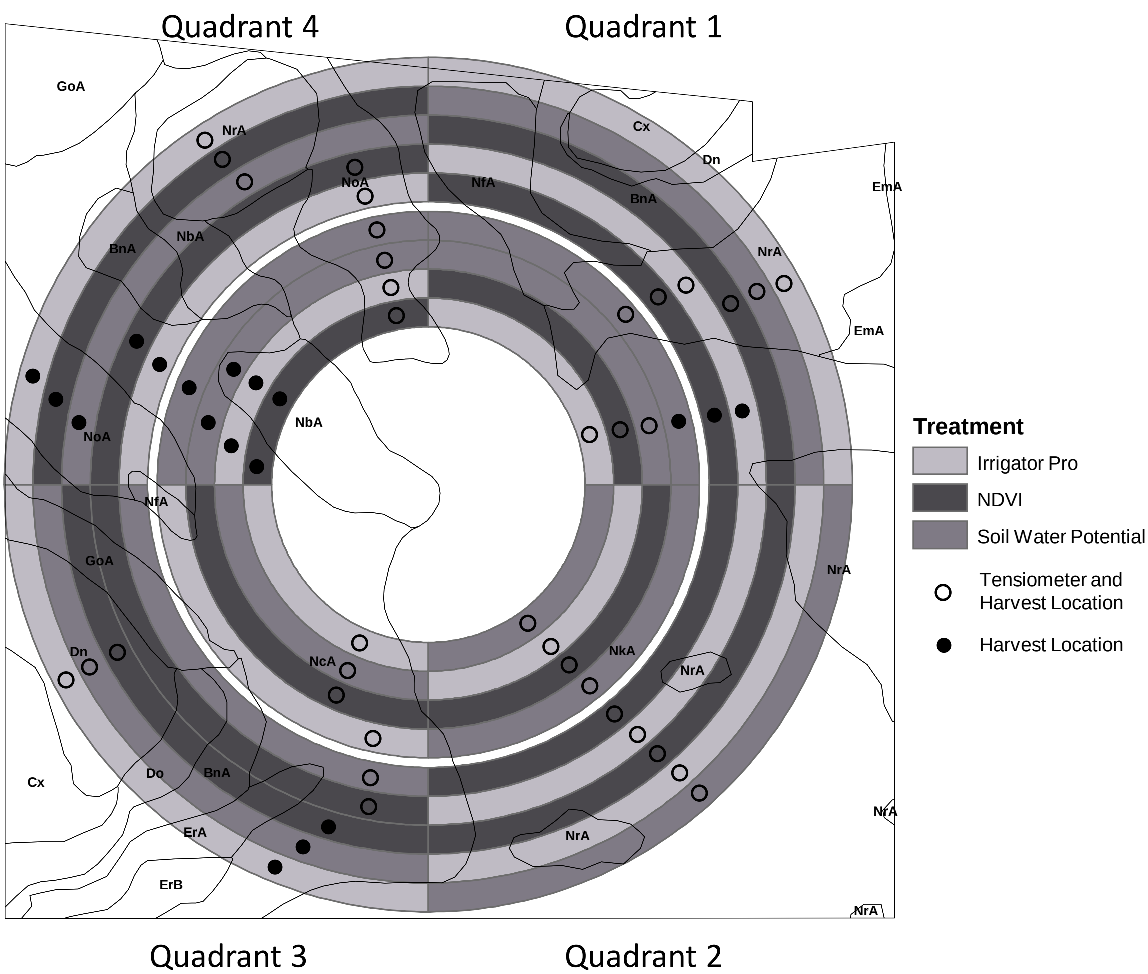

Figure 1. Plot map for the 2012-2014 irrigation study.

Soil water potentials were manually measured and tabulated at 36 locations (fig. 1) within the experiment. In each treatment and replication, tensiometers were installed in the predominate soil type within each plot at two depths (0.30 and 0.60 m). The predominate soil type in each plot was used to manage irrigation for the entire SWP treatment plot. Measurements were recorded at least three times each week. The 0.30 m tensiometers in the SWP and NDVI treatments were used to initiate irrigation applications. When the SWP of the SWP treatments decreased below -30 kPa, a 12.5 mm irrigation application was applied to that plot. Additionally, if the SWP decreased below -50 kPa, an additional 12.5 mm of irrigation was applied if the rainfall forecast was less than 50%. For the NDVI treatment plots, when the SWP decreased below -30 kPa and the 7-day calculated water balance (ET – rainfall) exceeded 12.5 mm, a 12.5 mm irrigation application was initiated. Irrigation for the Irrigator Pro for Corn expert system was initiated when the calculated available water in the soil was about 50% depleted. All irrigations were halted when the corn reached black layer each year.

Harvest Details: Corn grain yields were determined by weighing the grain harvested from a 6.1 m length of two rows near the center of each plot using a plot combine. A total of 54 yield samples were collected near the 36 tensiometer monitoring sites. Subsamples were collected from the plots and air-dried to obtain seed moisture content. Grain yields were corrected to 15.5% moisture. After yields and total water applied to each treatment were determined, the water use efficiency (WUE) was calculated by dividing the mean plot yield by the total water applied (irrigation + rainfall). The WUE values were reported in units of kg grain ha^{-1} mm^{-1} of water applied.

Statistical Analyses: All data were statistically analyzed in SAS (SAS Institute, Inc., Cary, N.C.) using Proc GLM. The experimental design was a randomized block design with twelve replicates. An initial analysis combined over all years indicated that the years were significantly different, so analysis was conducted on each year individually for yield and total water usage. Treatment means were separated using the Waller-Duncan k-ratio and Fisher’s least significant tests.

Results and Discussion

Rainfall: For the three-year study, the growing season (April to August) rainfalls were 468 mm in 2012, 620 mm in 2013, and 414 mm in 2014. In 2013 only two irrigations were required. In 2012, two to nine irrigations were required depending on treatment in late June and early July. The 2014 season required the greatest number of irrigation events (7 to 21 depending on treatment), and had greatest total irrigation depth.

Corn Yields: An overall analysis of variance for corn yield indicated that the growing year was the only significantly different variable. The average corn yields for the three-year study across the three irrigation treatments ranged from 10.3 to 16.2 Mg ha^{-1}. The 2012 overall yield (15.6 Mg ha^{-1}) was significantly greater than the overall yields of the other two years (table 1). Even though 2013 had the highest rainfall, it had a significantly lower yield (10.5 Mg ha^{-1}) and may be attributed to reduced nitrogen application in that year.

Because the corn yields for the three years were significantly different, we analyzed them individually. In 2012, the mean corn yield across all irrigation treatments was 15.6 Mg ha^{-1} and treatments were not significantly different (table 1). This indicated that all three irrigation treatments adequately provided enough water for the corn crop. In 2013, the mean treatment corn yields were not significantly difference and averaged 10.5 Mg ha^{-1}. It also had the greatest rainfall during the growing season with the least number of irrigation events (0 to 2 depending on treatment), yet it had the lowest mean yield of the three-year study. In 2014, the mean corn yields across irrigation treatments were not significantly different and had an overall mean yield of 13.5 Mg ha^{-1},. Year 2014 had the least cumulative rainfall for the three-year study and the greatest number of irrigation events.

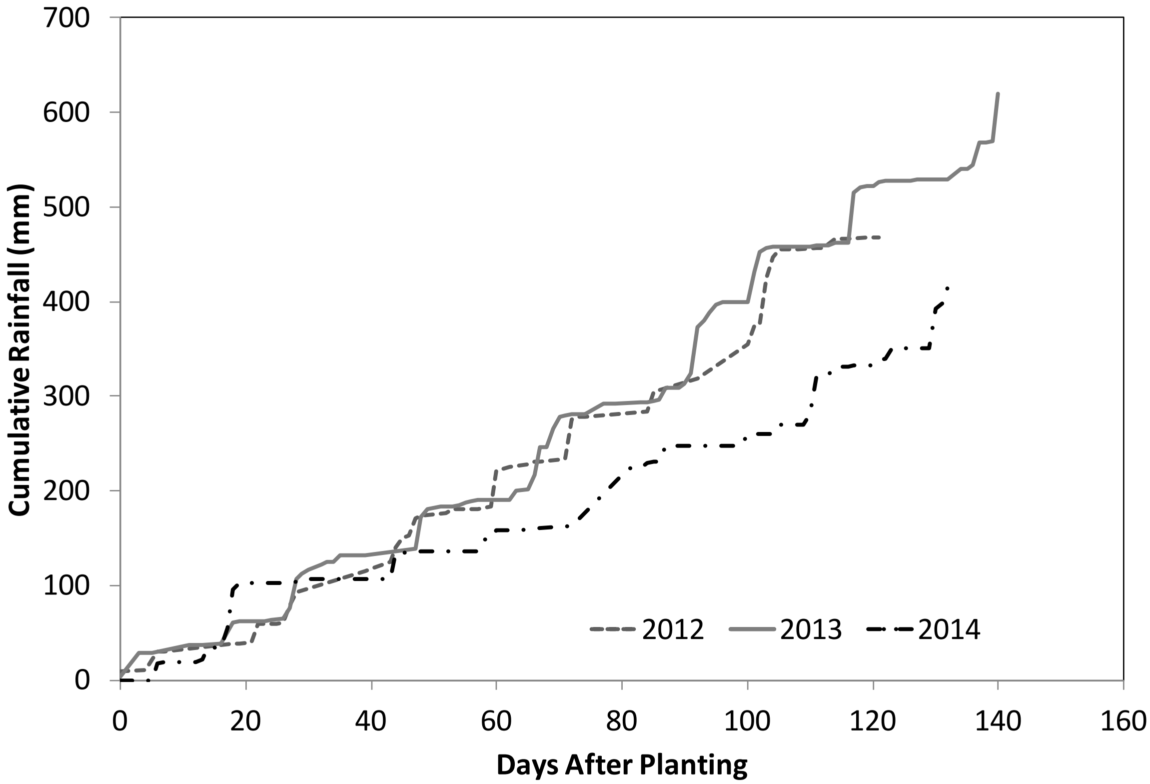

Figure 2. Growing season cumulative rainfall.

Based on the three-year study with different rainfall distributions throughout the growing seasons, each of the three full irrigation scheduling methods provided adequate supplemental irrigation to produce good to excellent corn yields for the region (Wiatrak, 2010).

Total Water, Irrigation, and WUE: The total water (rain + irrigation) received by the corn crop varied over the three years by irrigation treatment. The total water the corn crops received from 2012 to 2014 was 526, 627, and 570 mm, respectively, with 2012 to 2014 yearly mean irrigation water applied to the corn crop was 57, 7, and 156 mm, respectively (table 1). In only year 2012 were the total water and irrigation treatment mean depths significantly different. The Irrigator Pro treatment had significantly higher total water and irrigation water depth than the other treatments. The Irrigator Pro treatments typically called for more early-season irrigation events. The 2012-2014 WUE across irrigation treatments was 29.8, 16.8, and 23.8 kg ha^{-1} mm^{-1}, respectively and were significantly different.

Table 1. Mean corn yields, irrigation depths, and water use efficiencies for the three irrigation treatments.

Treatment	Yield [a] (Mg ha^{-1})			Irrigation (mm)			Water Use Efficiency (kg grain ha^{-1} mm^{-1})		
	N	Mean	SD	*N*	Mean	SD	*N*	Mean	SD
2012									
Irrigator Pro	18	16.2 a	1.2	18	76.9 a	27.3	18	29.7 a	2.9
NDVI	18	15.6 a	1.9	18	53.3 b	28.2	18	30.1 a	4.7
SWP	18	15.1 a	1.9	18	41.3 b	18.5	18	29.6 a	3.7
Year mean	54	15.6 A	1.7	54	57.2 B	28.8	54	29.8 A	3.8
2013									
Irrigator Pro	18	10.8 a	1.3	18	6.4 a	10.0	18	17.3 a	2.1
NDVI	18	10.5 a	2.6	18	7.8 a	6.9	18	16.7 a	4.2
SWP	17	10.3 a	1.7	18	7.8 a	9.9	17	16.5 a	2.7
Year mean	53	10.5 C	1.9	54	7.3 C	8.9	53	16.8 C	3.1
2014									
Irrigator Pro	18	13.3 a	1.7	18	163.7 a	29.8	18	23.0 a	3.0
NDVI	18	13.8 a	1.8	18	152.2 a	27.8	18	24.4 a	3.1
SWP	18	13.5 a	1.5	18	152.4 a	35.4	18	24.0 a	3.0
Year mean	54	13.5 B	1.7	54	156.1 A	31.1	54	23.8 B	3.0
Overall mean	161	13.3	2.7	162	73.5	66.8	161	23.5	6.2

[a] Year means across treatments followed by the same uppercase letter are not significantly different at the 5% level. Treatment means within a year followed by the same lowercase letter are not significantly different at the 5% level.

Conclusions

Corn was grown under variable-rate center-pivot irrigation for three years (2012-2014) to evaluate the potential of using vegetative indices and an expert system for managing spatial irrigations. These two methods were compared with irrigation management using soil water potentials. Rainfall during the three growing seasons varied widely. In 2013, only two irrigation events were required, while the 2014 growing season required 7 to 21 irrigation events depending on the plot.

The 2012 corn crop had the highest overall yield (15.6 Mg ha^{-1}) and was significantly greater than the other two years. In 2014, the overall mean yield was 13.6 Mg ha^{-1}, and even though 2013 had the highest rainfall, it had a significantly lower yield (10.5 Mg ha^{-1}).

The crop irrigation depths for the three years were significantly different and varied from an average of 156 mm in 2014, to 75 mm in 2012, to 7 mm in 2013. In 2012, the Irrigator Pro required significantly greater irrigation than the SWP or NDVI treatments. In 2013 and 2014, there were no significant differences in irrigation depth between the irrigation treatments. The WUE for the three irrigation treatments was significantly different for the three-year study, ranging from 29.8 kg ha^{-1} mm^{-1} in 2012, to 23.8 kg ha^{-1} mm^{-1} in 2014, and to 16.8 kg ha^{-1} mm^{-1} in 2013. However, for individual years, there were no significant differences in WUE among the irrigation treatments.

Overall, the NDVI and Irrigator Pro for Corn treatments managed irrigations as well as the traditional SWP-based treatment. Each of these irrigation treatments was able to adequately manage irrigation and produce adequate crop yields for the region and could be used effectively to manage irrigation under a variable-rate irrigation system.

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