IRRIGATION MANAGEMENT USING AN EXPERT SYSTEM, SOIL WATER POTENTIALS, AND VEGETATIVE INDICES FOR SPATIAL APPLICATIONS

K. C. Stone, P. J. Bauer, G. C. Sigua

ABSTRACT. *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. However, when compared to traditional irrigation systems, VRI systems require a higher level of management. 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 the Irrigator Pro for Corn expert system, measured soil water potential (SWP), and remotely sensed crop vegetative indices (NDVI) to estimate crop coefficients. These irrigation treatments were implemented over six soil types under a VRI system for three years. Corn yields differed among years; average yields were 15.6 Mg ha*$^{-1}$ *in 2012, 10.5 Mg ha*$^{-1}$ *in 2013, and 13.5 Mg ha*$^{-1}$ *in 2014. However, corn yields for the three irrigation treatments were not significantly different for any one year. The mean yearly irrigation applied in 2012, 2013, and 2014 was 57, 7, and 156 mm, respectively. The mean water use efficiency (WUE) over the three years was significantly different, with values of 29.8, 16.8, and 23.8 kg grain ha*$^{-1}$ *mm*$^{-1}$ *for 2012, 2013, and 2014, respectively. For each individual year, the WUE among irrigation treatments was not significantly different. For the six soils types, there were no significant differences for corn yield or WUE. The Irrigator Pro for Corn and NDVI treatments managed irrigations as well as the traditional SWP-based treatment under the VRI system from 2012 to 2014. Each of these irrigation treatments was able to adequately manage irrigation spatially and produce adequate crop yields for the region. Each of these irrigation management treatments could be used effectively to manage irrigations under a VRI system with different management zones.*

Keywords. *Irrigation management, Irrigation scheduling, Variable-rate irrigation.*

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, soil water availability, and landscape features but may also be used in response to site-specific crop water requirements. VRI systems are commercially available and have high grower interest. Center pivots with VRI systems have typically been managed for precision irrigation applications based on either the producers' past experience and knowledge of variability in their fields or by using other static parameters such as soil electrical conductivity (EC). Science-based information is needed on how to precision-apply water with these systems. Sadler et al. (2005) identified critical needs for site-specific irrigation research that included decision support systems for spatial water application and improved real-time monitoring of field conditions with feedback to irrigation systems.

Irrigation management for corn production in the southeastern U.S. is difficult because of the highly variable climate and typically low water holding capacity of the soils. Additionally, in the humid southeastern U.S., the high probability of growing season rainfall makes irrigation scheduling difficult. In years with a good distribution of rainfall during the growing season, little if any supplemental irrigation is needed. However, Sheridan et al. (1979) documented that there was a 50% chance of a 20-day drought during the annual growing season in the southeastern Coastal Plain. If a short drought occurred during critical corn growth stages, yield would be greatly reduced. Irrigation scheduling methods in the southeastern U.S. vary widely and range from the feel method (USDA-NRCS, 1998), to instrumentation to measure the soil water content or potential, to computer-based irrigation scheduling (Rhodes and Yonts, 2015).

More recently, decision support systems have been used to manage irrigation applications. Decision support systems can assist in determining both uniform and spatial water applications. Currently, there are no readily identified deci-

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The authors are **Kenneth C. Stone, ASABE Member,** Research Agricultural Engineer, **Philip J. Bauer,** Research Agronomist, and **Gilbert C. Sigua,** Research Soil Scientist, USDA-ARS Coastal Plains Soil, Water, and Plant Research Center, Florence, South Carolina. **Corresponding author:** Kenneth Stone, USDA-ARS, 2611 West Lucas St., Florence, SC 29501; phone: 843-669-5203; e-mail: ken.stone@ars.usda.gov.

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sion support systems for site-specific water management. However, the USDA-ARS National Peanut Laboratory in Dawson, Georgia, has developed and distributed an expert system (Irrigator Pro) for corn management (Davidson et al., 1998a). Irrigator Pro assists producers with irrigation management by integrating several factors, including soil type, yield potential, previous crop, cultivar, and planting date. During the growing season, the expert system requires inputs of rainfall and soil water potentials to recommend a decision on when and how much to irrigate depending on the upcoming 3 to 5 day rainfall probabilities.

Another 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 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) the Irrigator Pro for Corn expert system, (2) using measured soil water potentials, and (3) using remotely sensed crop vegetative indices to estimate crop coefficients.

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 (fig. 1) under the center-pivot irrigation system are highly variable (table 1). Three irrigation treatments were evaluated for their potential utilization for spatial irrigation management using the VRI system. The first irrigation treatment was based on the Irrigator Pro for Corn expert system that was developed by the USDA-ARS National Peanut Research Laboratory. This expert system has been tested extensively in uniformly irrigated fields (Davidson et al., 1998a, 1998b; 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 second 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 third 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. Hunsaker et al. (2003) used a slope of 1.49 to estimate crop coefficients for cotton. We chose to use a slope of 1.5 in calculating K_{cb} as a conservative estimate. We anticipate that the slope can be better estimated with additional research. These three treatments were randomized to ensure that each treatment included six common soils (table 1).

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). Variable-rate water applications were accomplished by using three manifolds in each segment; each manifold had nozzles sized to deliver 1×, 2×, or 4× of a base application depth at that location along the center-pivot length. All combinations of the three manifolds provided application depths of 0 through 7× of the base rate. The 7× depth was 12.7 mm when the outer tower was operated at 50% duty cycle. The manifolds were operated by individual solenoid valves controlled with a computer and programmable logic controller (PLC) (model 90-30, GE Fanuc, Charlottesville, Va.) that obtained positional (angular) data from the C:A:M:S management system (Valmont Industries, Inc., Valley, Neb.). A software control program written in Visual Basic (Microsoft, Redmond, Wash.) controlled the PLC using fixed positional data and user-supplied data stored in the computer and angular positional data from the center-pivot management system. A more detailed description of the water

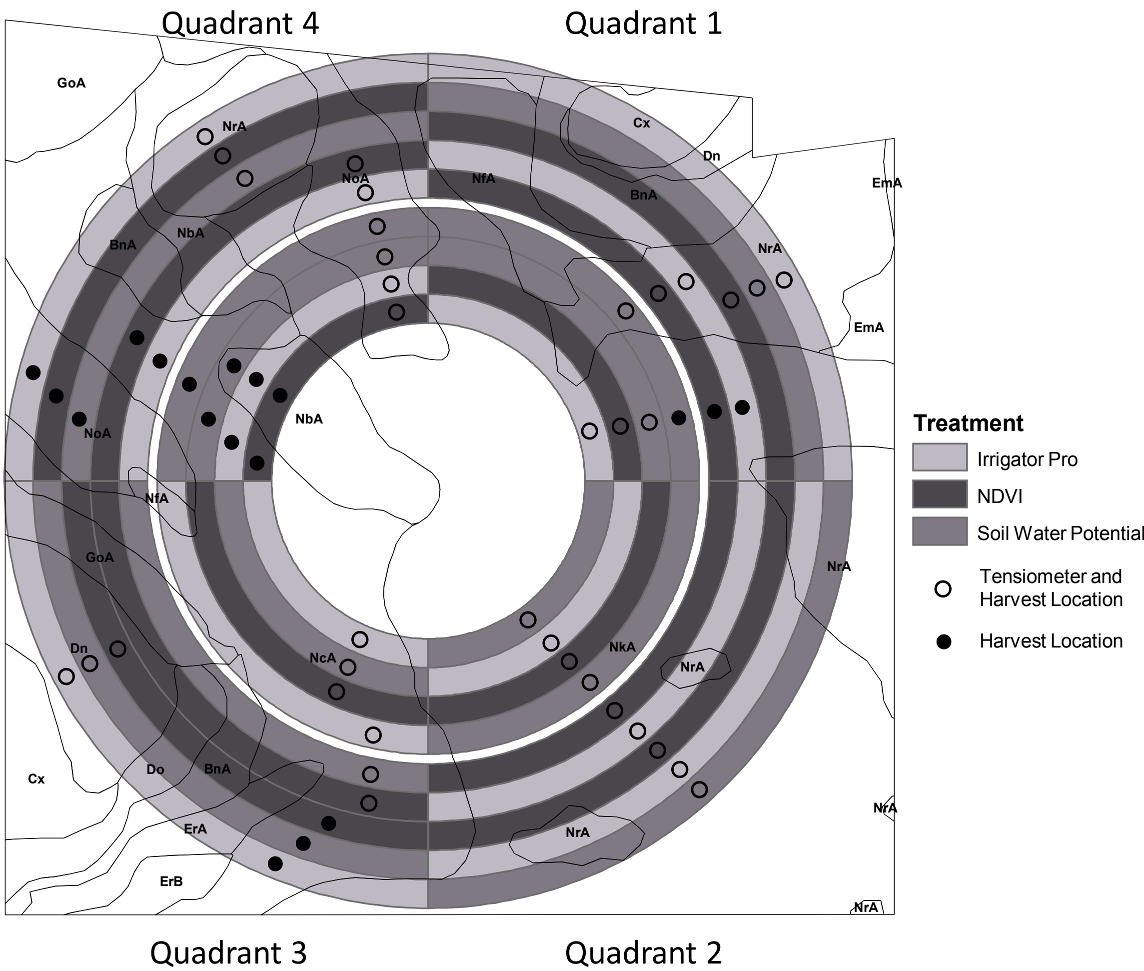

Figure 1. Plot map for the 2012-2014 irrigation study.

Table 1. Soil types and classification for the studied soils.

Symbol	Soil Classification
Dn	Dunbar loamy fine sand
NbA	Noboco loamy fine sand, moderately thick surface, 0% to 2% slopes
NcA	Noboco loamy fine sand, thick surface, 0% to 2% slopes
NkA	Norfolk loamy fine sand, moderately thick surface, 0% to 2% slopes
NoA	Norfolk loamy fine sand, thick surface, 0% to 2% slopes
NrA	Norfolk fine sandy loam, 1% to 2% slopes

delivery system may be found in Omary et al. (1997) and for the control system in Camp et al. (1998).

Crop Management

Each year, field preparation started with an application of glyphosate via a tractor-mounted sprayer to control winter weeds. Field tillage at corn planting consisted of in-row subsoiling. The corn (Dekalb 66-97 in 2012 and 2013, and Dekalb DKC66-97 in 2014) was planted in 76 cm rows in a circular pattern with a planting population of 79,000 seeds ha^{-1}. Each plot or pivot segment had 12 rows. The planting dates for the three years were 30 March 2012, 9 April 2013, and 4 April 2014. All nitrogen fertilizer, except preplant granular applications (25 kg ha^{-1} N), was applied via fertigation using a variable-rate injection pump (model 506-2, Ozawa R&D, Inc., Ontario, Ore.) that varied the injection rate based on the pivot instantaneous water flow rate. 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 an 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 were used for the crop coefficients (Bausch, 1993; Hunsaker et al., 2003; Glenn et al., 2011). The mean NDVI readings for the NDVI treatment plots were calculated, and crop coefficients were calculated by multiplying by a slope of 1.5. In 2012, mean 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 ($K_{cb\ end}$). Soil water potentials were manually measured and tabulated at 36 locations (fig. 1) within the experiment. In each treatment and replication, tensiometers (Soilmoisture Equipment Corp,, Santa Barbara, Cal.) 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 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%. The 0.60 m tensiometer was used to determine if the irrigations were reaching the subsoil. 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 an Almaco plot combine with a corn header (Almaco, Nevada, Iowa) on 10 September 2012, 16 September 2013, and 11 September 2014. A total of 54 yield samples were collected near the 36 tensiometer monitoring sites and in plots with multiple soils at additional locations within that plot. 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. The homogeneity of variance test was used to determine differences among the treatments using Bartlett's test in Proc GLM.

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. The historical cumulative rainfall in April through August was 533 mm (1981 to 2010; SCDNR, 2010). In each year of the study, the rainfall distribution pattern was different (figs. 2 and 3). The 2013 season had greater than normal rainfall in April, June, and July and only required irrigation on two days. The 2012 season had greater than normal rainfall in April, May, and July and required irrigations (2 to 9 irrigation events depending on treatment) in late June and early July. The 2014 season had greater than normal rainfall only in April, required the greatest number of irrigation events (7 to 21 depending on treatment), and had greatest total irrigation depth.

Corn Yields

The average corn yields for the three-year study across the three irrigation treatments ranged from 10.3 to 16.2 Mg ha^{-1}. An overall analysis of variance for corn yield indicated that the growing year was the only significant variable. The three-year mean corn yields for the three treatments were not significantly different (table 2). The 2012 overall yield (15.6 Mg ha^{-1}) was significantly greater than the overall yields of the other two years (table 3). Even though 2013 had the highest rainfall, it had a significantly lower yield (10.5 Mg ha^{-1}) than either 2012 or 2014 (15.6 and

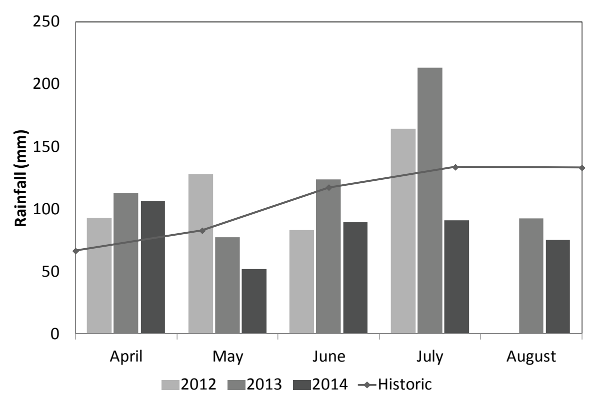

Figure 2. Growing season rainfall distribution.

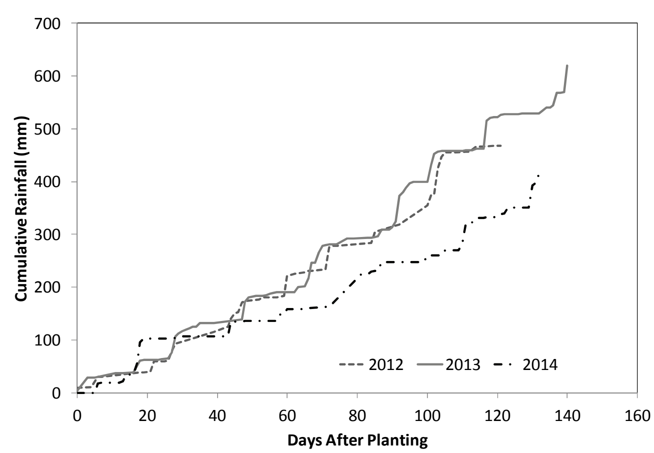

Figure 3. Growing season cumulative rainfall.

Table 2. Three-year overall mean corn yield, irrigation, total water usage, and water use efficiency.[a]

Treatment	Yield (Mg ha^{-1}) *N*	Yield Mean	Yield SD	Irrigation (mm) *N*	Irrigation Mean	Irrigation SD	Total Water (Irrigation + Rainfall) (mm) *N*	Total Water Mean	Total Water SD	Water Use Efficiency (kg ha^{-1} mm^{-1}) *N*	WUE Mean	WUE SD
Irrigator Pro	54	13.4 a	2.6	54	82.3 a	69.1	54	583.1 a	40.9	54	23.4 a	5.8
NDVI	54	13.3 a	3.0	54	71.1 b	65.0	54	571.9 b	49.3	54	23.7 a	6.8
SWP	53	13.0 a	2.6	54	67.1 b	66.6	54	567.9 b	53.8	53	23.5 a	6.2

[a] Within a column, means followed by the same letter are not significantly different at the 5% level.

Table 3. Mean corn yields (Mg ha^{-1}) for the three irrigation treatments across soil types.

Year and Treatment[a]	Dn *N*	Dn Mean	Dn SD	NbA *N*	NbA Mean	NbA SD	NcA *N*	NcA Mean	NcA SD	NkA *N*	NkA Mean	NkA SD	NoA *N*	NoA Mean	NoA SD	NrA *N*	NrA Mean	NrA SD	Overall Treatment Mean[b] *N*	Overall Mean	Overall SD
2012																					
Irrigator Pro	1	15.2	-	1	17.0	-	5	16.6	0.7	5	16.4	1.2	3	14.9	2.1	3	16.2	0.6	18	16.2 a	1.2
NDVI	1	15.1	-	1	14.5	-	5	16.2	1.8	5	15.4	2.5	3	17.0	1.7	3	14.1	1.1	18	15.6 a	1.9
SWP	1	14.9	-	1	17.2	-	5	16.2	2.6	5	14.8	0.9	3	14.7	0.7	3	13.2	1.4	18	15.1 a	1.9
Year mean	3	15.1 a	0.1	3	16.2 a	1.5	15	16.4 a	1.8	15	15.5 a	1.7	9	15.5 a	1.8	9	14.5 a	1.6	54	15.6 A	1.7
2013																					
Irrigator Pro	1	10.8	-	1	13.3	-	5	10.9	1.4	5	10.1	1.0	3	10.8	0.7	3	11.1	1.9	18	10.8 a	1.3
NDVI	1	10.1	-	1	13.4	-	5	10.1	4.6	5	10.4	1.4	3	10.6	2.0	3	10.2	2.1	18	10.5 a	2.6
SWP	1	11.3	-	1	11.9	-	4	10.9	0.7	5	9.3	1.1	3	10.1	3.2	3	10.4	2.0	17	10.3 a	1.7
Year mean	3	10.7 a	0.6	3	12.9 a	0.8	14	10.6 a	2.7	15	10.0 a	1.2	9	10.5 a	2.0	9	10.6 a	1.8	53	10.5 C	1.9
2014																					
Irrigator Pro	1	11.2	-		15.8	-	5	14.1	2.0	5	13.5	1.3	3	12.5	1.3	3	12.4	1.3	18	13.3 a	1.7
NDVI	1	14.2	-	1	14.5	-	5	13.6	2.0	5	15.0	1.6	3	12.7	0.4	3	12.8	2.7	18	13.8 a	1.8
SWP	1	13.5	-	1	11.4	-	5	13.7	1.4	5	14.3	1.3	3	12.5	2.3	3	13.9	0.8	18	13.5 a	1.5
Year mean	3	13.0 a	1.6	3	13.9 a	2.2	15	13.8 a	1.7	15	14.3 a	1.5	9	12.6 a	1.3	9	13.0 a	1.7	54	13.5 B	1.7
Overall soil mean	9	12.9	2.1	9	14.3	2.1	44	13.7	3.1	45	13.2	2.8	27	12.9	2.7	27	12.7	2.3	161	13.3	2.7

[a] Year means followed by the same capital letter are not significantly different at the 5% level, and yearly means across treatments followed by the same lowercase letter are not significantly different at the 5% level.

[b] Overall treatment means followed by the same capital letter are not significantly different at the 5% level, and yearly means across soil types followed by the same lowercase letter are not significantly different at the 5% level.

13.5 Mg ha^{-1}, respectively). The lower overall yield in 2013 may be attributed to reduced plant-available nitrogen in the soil profile due to greater than normal rainfall in June and July.

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 individual yields ranged from 13.2 to 17.2 Mg ha^{-1}. The 2012 irrigation treatment corn yields were not significantly different (table 3). This indicated that all three irrigation treatments adequately provided enough water for the corn crop. Additionally, the yields were analyzed across six soil types with various water holding capacities. The mean yields across soil types were not significantly different, and the irrigation treatment yield means for the individual soils were also not significantly different.

In 2013, the mean corn yields across all treatments and soil types were 10.5 Mg ha^{-1}, and individual yields ranged from 9.3 to 13.4 Mg ha^{-1} (table 3). This year had the greatest rainfall during the growing season and the least number of irrigation events, yet it had the lowest mean yield of the three-year study. Due to above-normal rainfall, the individual plots received only 0 to 2 irrigations with irrigation depths from 0 to 25 mm. The 2013 mean corn yields across soil types ranged from 10.0 to 12.9 Mg ha^{-1} and were not significantly different. Treatment yields within a soil type were also not significantly different.

In 2014, the mean corn yields across all soil types and irrigation treatments were 13.5 Mg ha^{-1}, and individual yields ranged from 11.2 to 15.8 Mg ha^{-1}. The 2014 growing season had the least cumulative rainfall for the three-year study and the greatest number of irrigation events. The mean corn yields across soil types ranged from 12.6 to 14.3 Mg ha^{-1} and were not significantly different. The treatment yields within a soil type were also not significantly different. In a four-year study on the same field growing corn under rainfed conditions, Karlen et al. (1990) found significant yield differences across these soil mapping units. Later, in a three-year study evaluating the spatial variation of corn response to different levels of irrigation, Sadler et al. (2002) found significant differences in yield response across these soil mapping units. Over our three-year study, the three irrigation treatments appeared to overcome the earlier yield variability on these soils.

For the three-year study, the overall yields and each year's corn yields were evaluated for homogeneity of variance to determine if there were greater variances in yields between the treatments and soils within individual plots compared to variances between plots. In 2012 and 2014, there were no significant yield variances between treatments or soils. In 2013, there were significant differences in yield variances for both the treatments ($p = 0.01$) and the soils ($p = 0.03$). Similar variability results for corn (and other crops) were observed by Sadler et al. (1998) and Karlen et al. (1990), where the reported variability within soil mapping units was as great as the variability among soil mapping units.

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 crops varied over the three years by irrigation treatment and soil type. An overall analysis of the three-year study indicated that the soil type, treatment, and year were significantly different for both total water and irrigation (table 4). The three-year mean irrigation and total water the crop received was significant, with Irrigator Pro requiring greater irrigation than the other treatments (table 2). The total water the corn crops received from 2012 to 2014 was 526, 627, and 570 mm, respectively (table 4). The 2012 to 2014 yearly mean irrigation water applied to the corn crop was 57, 7, and 156 mm, respectively (table 4). These yearly irrigation depths applied were associated with the total seasonal rainfall and rainfall distributions during the growing seasons. The overall three-year WUE was not significantly different (table 2), yet each year was significantly different (table 5). The 2012-2014 WUE was 29.8, 16.8, and 23.8 kg ha^{-1} mm^{-1}, respectively. Although 2012 and 2014 had higher WUE than 2013, the three irrigation treatments were not significantly different. However, the WUE for soil type was significantly different in the overall analysis.

Because the yearly total water and irrigation depths were significantly different, the treatments for each year were analyzed. In 2012, the total water and irrigation treatment mean depths were significantly different. The Irrigator Pro treatment had significantly higher total water and irrigation water depth than the other treatments (total water was 546 mm versus 522 and 510 mm for the NDVI and SWP irrigation treatments, respectively; irrigation was 77 mm versus 53 and 41 mm for the NDVI and SWP treatments, respectively). The Irrigator Pro treatments typically called for more early-season irrigation events. The mean irrigation depths for the different soils types varied from 48 to 72 mm and were not significant ($p = 0.05$). The 2012 WUE values for the irrigation treatments were not significantly different, but the WUE values were significant at the 10% level, with means ranging from 26.9 to 32.6 kg ha^{-1} mm^{-1}.

In 2013, little supplemental irrigation was needed, mostly due to adequate growing season rainfall. Due to the adequate rainfall, there were no significant differences in total water or irrigation depths applied for the three irrigation

Table 4. Mean irrigation depths (mm) for the three irrigation treatments across soil types.

Year and Treatment[a]	Soil Type																		Overall Treatment Mean		
	Dn			NbA			NcA			NkA			NoA			NrA					
	N	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD
2012																					
Irrigator Pro	1	88.9	-	1	50.8	-	5.0	73.7	22.7	5.0	69.9	31.1	3	72.0	36.7	3	103.7	18.3	18	76.9	27.3
NDVI	1	59.7	-	1	19.1	-	5	39.9	19.9	5	70.4	30.6	3	36.0	29.3	3	74.1	19.4	18	53.3	28.2
SWP	1	69.9	-	1	19.1	-	5	47.0	18.8	5	43.2	21.3	3	36.0	14.7	3	31.8	12.7	18	41.3	18.5
Year mean	3	72.8 a	14.8	3	29.6 b	18.3	15	53.5 ab	24.3	15	61.1 ab	29.1	9	48.0 ab	30.5	9	69.9 a	34.6	54	57.2 B	28.8
2013																					
Irrigator Pro	1	0.0	-	1	0.0	-	5	2.5	5.7	5	10.2	13.9	3	4.2	7.3	3	12.7	12.7	18	6.4	10.0
NDVI	1	15.2	-	1	2.5	-	5	7.1	7.5	5	12.2	6.8	3	2.5	0.0	3	5.9	8.2	18	7.8	6.9
SWP	1	25.4	-	1	0.0	-	5	10.2	10.6	5	7.6	11.4	3	0.0	0.0	3	8.5	7.3	18	7.8	9.9
Year mean	3	13.5 a	12.8	3	0.8 a	1.5	15	6.6 a	8.2	15	10.0 a	10.4	9	2.3 a	4.1	9	9.0 a	8.9	54	7.3 C	8.9
2014																					
Irrigator Pro	1	139.7	-	1	152.4	-	5	165.1	32.4	5	149.9	24.4	3	169.3	40.8	3	190.5	25.4	18	163.7	29.8
NDVI	1	135.7	-	1	157.5	-	5	132.2	26.3	5	158.6	16.5	3	153.2	45.2	3	177.8	19.4	18	152.2	27.8
SWP	1	165.1	-	1	152.4	-	5	149.9	20.9	5	127.0	26.9	3	156.6	7.3	3	190.5	66.0	18	152.4	35.4
Year mean	3	146.8 a	15.9	3	154.1 a	2.9	15	149.0 a	28.6	15	145.2 a	25.4	9	159.7 a	31.6	9	186.3 a	37.2	54	156.1 A	31.1
Overall soil mean[b]	9	77.7 ab	59.2	9	61.5 b	71.1	45	69.7 b	63.7	45	72.1 ab	60.7	27	70.0 b	71.7	27	88.4 a	80.2	162	73.5	66.8

[a] Year means across treatments followed by the same lowercase letter are not significantly different at the 5% level, and yearly overall treatment means followed by the same capital letter are not significantly different at the 5% level.

[b] Overall soil means followed by the same lowercase letter are not significantly different at the 10% level.

Table 5. Mean water use efficiency (kg grain ha^{-1} mm^{-1}) for the three irrigation treatments across soil types.

Year and Treatment[a]	Soil Type																		Overall Treatment Mean		
	Dn			NbA			NcA			NkA			NoA			NrA					
	N	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD
2012																					
Irrigator Pro	1	27.2	-	1	32.7	-	5	30.7	1.1	5	30.5	3.2	3	27.8	5.2	3	28.4	1.1	18	29.7	2.9
NDVI	1	28.7	-	1	29.8	-	5	31.9	3.2	5	28.9	6.1	3	33.9	5.2	3	25.9	1.9	18	30.1	4.7
SWP	1	27.7	-	1	35.3	-	5	31.5	5.0	5	28.9	2.3	3	29.2	2.2	3	26.4	2.8	18	29.6	3.7
Year mean	3	27.8 ab	0.8	3	32.6 a	2.8	15	31.4 ab	3.3	15	29.4 ab	4.0	9	30.3 ab	4.7	9	26.9 b	2.1	54	29.8 A	3.8
2013																					
Irrigator Pro	1	17.5	-	1	21.5	-	5	17.5	2.3	5	16.0	1.4	3	17.4	1.1	3	17.6	2.9	18	17.3	2.1
NDVI	1	15.9	-	1	21.5	-	5	16.2	7.3	5	16.5	2.2	3	17.0	3.2	3	16.3	3.2	18	16.7	4.2
SWP	1	17.5	-	1	19.2	-	4	17.5	1.2	5	14.9	1.8	3	16.3	5.2	3	16.6	3.3	17	16.5	2.7
Year mean	3	17.0 a	0.9	3	20.7 a	1.3	14	17.0 a	4.3	15	15.8 a	1.9	9	16.9 a	3.2	9	16.8 a	2.8	53	16.8 C	3.1
2014																					
Irrigator Pro	1	20.2	-	1	27.9	-	5	24.3	3.2	5	23.9	2.5	3	21.5	2.1	3	20.4	1.4	18	23.0	3.0
NDVI	1	25.8	-	1	25.3	-	5	24.9	3.3	5	26.2	2.3	3	22.4	1.2	3	21.6	4.6	18	24.4	3.1
SWP	1	23.4	-	1	20.2	-	5	24.2	2.4	5	26.4	3.0	3	21.9	4.2	3	23.1	1.1	18	24.0	3.0
Year mean	3	23.1 ab	2.8	3	24.5 ab	3.9	15	24.5 ab	2.8	15	25.5 b	2.7	9	21.9 ab	2.5	9	21.7 b	2.7	54	23.8 B	3.0
Overall soil mean[b]	9	22.6 bc	5.0	9	25.9 a	5.8	44	24.5 ab	6.8	45	23.6 abc	6.5	27	23.0 ac	6.6	27	21.8 c	4.9	161	23.5	6.2

[a] Year means across treatments followed by the same lowercase letter are not significantly different at the 5% level, and yearly overall treatment means followed by the same capital letter are not significantly different at the 5% level.

[b] Overall soil means for individual soils followed by the same lowercase letter are not significantly different at the 5% level.

treatments or across soils types. Irrigations were only applied on two days in late June when the SWP reached <-30 kPa. The maximum irrigation depth applied was 25 mm, while some soil types and treatments received no irrigation. The 2013 overall mean WUE was 16.8 kg ha^{-1} mm^{-1} and was not significantly different for irrigation treatment or soil type.

In 2014, the rainfall was below normal throughout most of the growing season and overall required the greatest irrigation depth. The total water applied and irrigation depths were not significantly different across soil types or irrigation treatments. The 2014 mean irrigation depth applied was 156 mm, and individual treatment and soil type depths ranged from 127 to 191 mm. The overall mean WUE in 2014 was 23.8 kg ha^{-1} mm^{-1} and had no significant differences for irrigation treatment. The WUE values for the soil types ranged from 21.7 to 25.5 kg ha^{-1} mm^{-1} and were significantly different.

The WUE values we observed were similar to previously reported WUE values for corn. In eastern Colorado, Benjamin et al. (2015) reported irrigated WUE values ranging from 10 to 22 kg grain ha^{-1} mm^{-1}, and Kiniry et al. (2008) reported WUE values ranging from 14 to 25 kg grain ha^{-1} mm^{-1} in regional simulations studies. In Nebraska, Sadras et al. (2012) reported WUE values ranging from 27 to 37 kg grain ha^{-1} mm^{-1} in more intensively managed fields using center pivots.

Conclusions

Corn was grown under variable-rate center-pivot irrigation for three years (2012-2014) to evaluate the potential of using an expert system and vegetative indices 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.

Over the three-year study, the average corn yields across the three irrigation treatments ranged from 10.3 to 16.2 Mg ha^{-1}. An overall analysis of variance for corn yield indicated that the year was the only significant variable. 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 Irrigator Pro for Corn and NDVI 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 with different management zones.

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