POTENTIAL WATER CONSERVATION USING SITE-SPECIFIC VARIABLE RATE IRRIGATION

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ABSTRACT. *Site-specific variable-rate irrigation (VRI) systems can be used to spatially manage irrigation within sub-field-sized zones and optimize spatial water use efficiency. The goal of the research is to provide farmers and consultants a tool to evaluate the potential benefits of implementing VRI. The specific objective of this research is to evaluate the potential water savings using VRI management compared with uniform irrigation management to maintain soil water holding capacity above 50% depletion using two irrigation scenarios: 1) a standard 12.5 mm irrigation per application; and 2) an application to refill the soil profile to field capacity. A 21-year simulation study was carried out on a selected field with varying degrees of soil and topographic variability. The simulated field had 12 soil mapping units with water holding capacities in the top 0.30-m ranging from 42 to 70 mm. The 21-year simulation covering all weather conditions for each soil produced only two significantly different irrigation management zones for scenario 1, and for scenario 2 only one management zone. However, when the 21-year period was divided into periods with different ratios of rainfall to reference evapotranspiration, the simulations identified 1 to 5 management zones with significantly different irrigation requirements. These results indicate that variable rate irrigation system design and management should not be solely based on long term average weather conditions. Years with differing weather conditions should be used for potentially identifying management zones for VRI systems. Irrigation application depths between management zones ranged from 17 to 38 mm. However, when the actual soil areas of the study field were utilized to calculate the total volume of irrigation water applied, it resulted in an increase in water usage in the 2 and 4 management zones ranging from -1.2% to 5.8%. Water usage with VRI over uniform irrigation was greater by -1.6% to 6.8% in the 12.5 mm irrigations and by -1.2% to 2.2% for the field capacity irrigations*

Keywords. *Management zones, Precision farming, Variable-rate irrigation, Water conservation.*

Variable rate irrigation (VRI) systems have the potential to conserve water by spatially allocating limited water resources. Spatial water applications attempt to overcome site-specific problems that include spatial variability in topography, soil type, soil water availability, and landscape features. The VRI systems can apply water to crops based on spatial crop requirements, thus, they may be an important asset in fields that have highly variable soil with different water holding capacities.

Recent droughts throughout the United States have highlighted the delicate balance that faces agricultural production in competition with urban, industry, and environmental water uses (Stone et al., 2010). Under these drought conditions, VRI systems may be utilized for water conservation. Sadler et al. (2005) outlined opportunities for conservation including situations where non-cropped areas exist in a field for which irrigation can be turned completely off; situations where a reduced irrigation amount provides specific benefits; and finally, situations where optimizing irrigation amount to adapt to spatial productivity provides quantitative benefits.

Water conservation using VRI systems has been demonstrated in situations where water is shut off in response to physical features and to reduce the overlap from one system to another (Sadler et al., 2005). In these situations, water conservation would be impacted by the extent of the non-cropped areas or the amount of irrigation system overlap. Non-cropped areas may include rock outcrops, field ditches, wetlands or depressions included in the field, and field roads or public roads adjacent to irrigation fields. In production fields, they also addressed the potential of VRI to adapt to spatial soil infiltration rates and soil water storage capacities to avoid runoff or potential ponding in field portions. Water

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collected or ponded in lower lying areas is likely to be a major contributor to nutrient leaching and may create unfavorable growing conditions. Additionally, runoff due to excess irrigation could result in sediment transport offsite or relocation within the field area.

Although VRI systems have been shown to conserve water in the examples above, there is little scientific information documenting the capability of a VRI system to conserve water for crop production (Evans et al., 2013). A few multi-season field studies investigated the potential water savings using VRI versus Uniform irrigation (UI). In Idaho, King et al. (2006) compared VRI to UI in potato production over two years and found no significant difference in yield or water use. In the first year of their study, VRI treatment water application depths ranged from 14% less irrigation water applied to 19% greater irrigation water applied. In the second year, VRI treatment water application depths ranged from 18% less to 10% greater water application. In Mississippi, Sui and Yan (2017) compared VRI and UI for corn and soybean production and reported VRI used 25% less water with no overall significant difference in yields.

Most studies evaluating the benefits of VRI have utilized modeling efforts to compare crop yields under VRI and conventional UI management. In Evans and King (2012), they reported on several simulation studies examining crop production under both VRI and UI. Using 30 years of climate data, Ritchie and Amato (1990) simulated water use and corn yields for VRI and UI based on low, intermediate, and high soil water holding capacity management zones. They found that UI resulted in yield losses and/or excessive water applications due to under irrigation in some areas and over irrigating in other areas. They concluded VRI was a better management option based on yields, but it did not result in overall water savings. In Georgia, Nijbroek et al. (2003) conducted a 25-year soybean simulation study comparing VRI and UI for water use, drainage, and yields. They used five irrigation management zones based on soil available water holding capacity. Although there were yearly differences in irrigation amounts, overall for the 25-year study, there were not significant differences in yield, water use, or drainage. In Germany, Al-Kufaishi et al. (2006) used a daily soil water balance model to simulate water use for sugar beet production with management zones delineated based on soil available water holding capacity. Using 20-mm applications per required irrigation, they reported 13% lower water usage in VRI versus UI. In New Zealand, Hedley and Yule (2009) reported VRI water savings of 20% to 26% compared to UI in a three-year simulation on pasture and corn fields.

In a three-year combined field and spatial interpolation study, Sadler et al. (2002) measured the yield response of corn to irrigation across soil mapping units under a 6-ha VRI system. They used the spatially measured yield response to extrapolate the potential water savings using VRI management. They developed spatial soil-specific water production functions and extrapolated whole-field responses to various irrigation application rates. They reported a mean water savings of 8% from actual UI irrigation practices. Additionally, they calculated VRI water savings of 19% compared to ideal UI water management practices and 21% for a yield-maximizing UI practice (Sadler et al., 2005).

In this research, we used the field site from Sadler et al. (2002) to evaluate the potential for water conservation with VRI using a water balance approach. The field site had 12 soil mapping units with highly variable soils. Our specific objective was to evaluate the potential water savings using VRI management compared to uniform irrigation (UI) management using a simple water balance modeling approach. We evaluated and compared UI management with VRI management with two and four management zones, and also using the 12 individual soil types as individual management zones.

Methods

Field Site Descriptions

A 6-ha field with highly variable soils and a history of spatially managed crop production was selected to simulate water requirements for a corn crop (Sadler et al., 2002). Soil at this site had been mapped on a 1:1200 scale by USDA-NRCS staff in 1984 (USDA-SCS, 1984; fig. 1). Brief descriptions of the 12 soil map units are shown in table 1. The water holding capacity for these soils was estimated using the soil properties in the DSSAT soils database (Jones et al., 2003), from previous modeling research by Sadler et al. (2000), and from Peele et al. (1970). The soil had a wide range of water holding capacities (table 1). The water holding capacities in the top 0.30-m of the soils ranged from approximately 42 to 70 mm. We assumed that each soils' potential productivity was equal in these simulations.

Crop Management Simulation

These soils were used in a 21-year water balance simulation to maintain adequate soil moisture in the top 0.30 m of

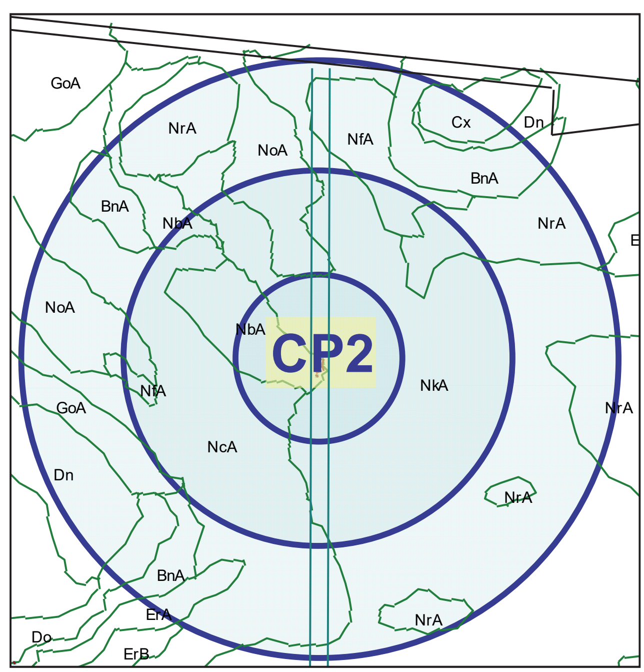

Figure 1. Diagram of field site with highly variable soils used in the simulation study.

Table 1. Description of soils and soil properties in the top 0.3-m located under the variable-rate irrigation system at Florence, SC (after Sadler et al., 2002).

Symbol	Soil Classification	Water Holding Capacity (mm)	Field Capacity (m^3/m^3)	Wilting Point (m^3/m^3)	Saturation (m^3/m^3)	Field area (m^2)
BnA	Bonneau loamy fine sand (lfs), 0% to 2% slopes	42.3	0.121	0.045	0.277	3205.8
Cx	Coxville loam	67.6	0.254	0.133	0.336	659.0
Dn	Dunbar lfs	60.0	0.169	0.073	0.295	2299.5
Do	Dunbar lfs, overwash	59.5	0.169	0.073	0.295	665.00
ErA	Emporia fine sandy loam (fsl), 1% to 2% slopes	59.5	0.156	0.056	0.270	555.6
GoA	Goldsboro lfs, 0% to 2% slopes	69.8	0.170	0.061	0.27	1291.4
NbA	Noboco lfs, moderately thick surface, 0% to 2% slopes	57.7	0.153	0.056	0.261	2898.3
NcA	Noboco lfs, thick surface, 0% to 2% slopes	42.8	0.145	0.055	0.261	10992.6
NfA	Noboco fsl, 1% to 2% slope	50.7	0.206	0.11	0.301	2251.2
NkA	Norfolk lfs, moderately thick surface, 0% to 2% slopes	49.3	0.137	0.056	0.260	22639.2
NoA	Norfolk lfs, thick surface, 0% to 2% slopes	47.5	0.125	0.053	0.26	4198.8
NrA	Norfolk fsl, 1% to 2% slopes	42.8	0.238	0.144	0.327	5919.7

the soil profile. Based on past experiences, it was estimated that the maximum allowable soil water depletion level for corn production in the region was 50%. Two irrigation scenarios were simulated when the maximum allowable water depletion level occurred: 1) a 12.5-mm irrigation was applied; and 2) an irrigation to refill the soil profile to field capacity. The daily simulated water balance was calculated as:

$$S_{i+1} = S_i + R_i + I_i - ET_{ci} - RO_i - D_i$$

where i represents the day, S was the soil water storage, R was the rainfall, I was the irrigation, ET_c the crop evapotranspiration, RO the runoff, and D the drainage. In the simulation, when the soil storage exceeded saturation, the excess was considered runoff. Drainage was calculated as the difference between maximum soil water holding capacity (field capacity) and saturation. Crop evapotranspiration was calculated based on the ASCE standardized reference evapotranspiration (ET_o) equation (Allen et al., 2005) method for short grass and crop coefficients for a corn crop. The field corn crop coefficients used in the simulations were $K_{cb\ init} = 0.15$, $K_{cb\ mid} = 1.15$, and $K_{cb\ end} = 0.5$ (FAO-56: Allen et al., 1998). The weather parameters were collected from an on-site weather station. In the simulations, the growing season was from 31 March to 6 August. The growing season rainfall was highly variable during the 21-year simulation period (fig. 2) and encompassed both wet and drought years. To account for highly variable growing season rainfall, we calculated the ratio of growing season cumulative rainfall to cumulative ET_o (Rainfall/ET_o). In addition to simulations covering all years, we estimated the irrigation requirements for years with the Rainfall/ET_o ratios of <50%, 50% to 60%, 60% to 75%, and >75%. The years with Rainfall/ET_o ratio <50% were 1992, 1993, 1999, 2002, and 2007. The years with Rainfall/ET_o ratio between 50% and 60% were 1994, 1998, 2001, 2006, and 2011. The years with Rainfall/ET_o ratio between 60% and 75% were 1995, 1997, 2000, 2004, and 2008. The years with Rainfall/ET_o ratio >75% were 1996, 2003, 2005, 2009, 2010, and 2012.

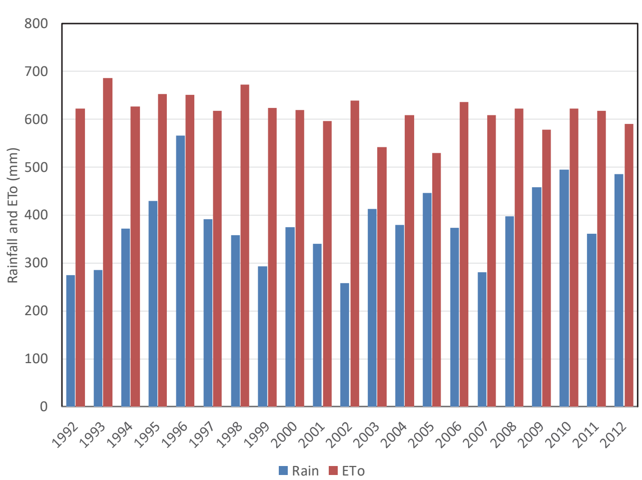

Figure 2. Cumulative seasonal rainfall and potential evapotranspiration (ETo) for the 21-year study period in Florence, South Carolina.

Management Zones

To simulate the VRI crop management of the field site, we used four irrigation scenarios. These irrigation scenarios included: 1) simulations using each individual soil mapping unit as a management zone; 2) simulations using two management zones grouping soils with similar water holding capacities (zone 1: BnA, NcA, NrA, NoA, NfA, NkA and zone 2: NbA, ErA, Dn, Cx, GoA); 3) simulations with four management zones (zone 1: BnA, NcA, NrA; zone 2: NoA, NkA, NfA; zone 3: NbA; zone 4: ErA, Dn, Cx, GoA). Since the Dn and Do soils had approximately the same water holding capacity, they were combined for the simulations. These simulations of various management zones were then compared to 4) a uniform irrigation using the soil type with the largest area in the field to control irrigation applications. All irrigation simulations started with a planting date of 31 March (day of year 90) and ended on 6 August (day of year 218).

Statistical Analyses

All simulation results were analyzed in SAS (SAS Institute, Inc. Cary, N.C.) using Proc GLM. The analyses compared the irrigation water applied for each soil and irrigation means were separated using the Waller-Duncan k-ratio and Fisher's least significant (LSD) tests at the 95% confidence level.

Results

Scenario 1, 12.5 mm Irrigation

The simulation results for the individual soils over the 21-year period produced irrigation amounts ranging from

Table 2. Simulated average irrigation requirements for the for 12 soil maps units for all years and for the years with different levels of Rainfall/ETo Ratio's using 12.5 mm irrigation applications.

	Rainfall/ET_o Ratio													All Years		
	<50%			50% to 60%			60% to 75%			>75%						
	Irrigation (mm)															
Soil	N[a]	Mean	Std Dev	n	Mean	Std Dev	n	Mean	Std Dev	n	Mean	Std Dev	n	Mean	Std Dev	
BnA	26	320 A[b]	38	23	293 A	36	23	283 A	19	17	215 A	37	22	274 A	52	
Cx	23	288 D	42	20	250 D	41	19	238 DE	20	13	163 E	44	18	231 B	60	
Dn	24	298 C	44	21	263 C	42	20	245 CD	21	15	181 D	41	19	244 AB	57	
ErA	24	300 C	42	21	263 C	42	20	245 CD	21	15	181 D	41	20	244 AB	57	
GoA	23	288 D	42	20	250 D	41	19	235 E	19	13	163 E	44	18	230 B	60	
NbA	24	300 C	42	21	268 C	37	20	248 C	22	15	192 C	38	20	249 AB	53	
NcA	26	320 A	38	23	293 A	36	23	283 A	19	17	215 A	37	22	274 A	52	
NfA	25	313 B	42	22	278 B	37	21	260 B	24	16	204 B	31	21	261 AB	52	
NkA	25	313 B	42	23	283 B	34	21	260 B	24	17	206 AB	34	21	263 AB	52	
NoA	25	318 AB	40	23	283 B	34	21	265 B	24	17	208 AB	37	21	266 A	52	
NrA	26	320 A	38	23	293 A	36	23	283 A	19	17	215 A	37	22	274 A	52	
Maximum Difference		32.5			42.5			47.5			52.1			44		
Maximum Difference%		11%			17%			20%			32%			19%		
No. of Significant Zones		4			4			5			5			2		

[a] Average number of irrigations per year.

[b] Irrigation depths in a column with a different letter was significantly different at the 95% level.

230 mm for the soils with the highest water holding capacity (WHC) to 274 mm for the soils with the lowest WHC (table 2). The simulation results produced two groupings (or potential management zones) of significantly different irrigation amount ranges for the soils studied. In these two groups, the four soils with the lowest WHC (BnA, NcA, NrA, NoA) required significantly greater irrigation than the two soils with the highest WHC (Cx, GoA). Irrigation amounts for the other five soils were not significantly different from either grouping.

The simulated years were then divided into years representing different rainfall totals as defined by the Rainfall/ET_o ratio. We divided these years into four groups of the Rainfall/ET_o ratios representing different degrees of drought conditions and then simulated irrigation amounts for the individual soils (table 2). Irrigation depths for the most severe drought conditions with Rainfall/ET_o ratios less than 50%, ranged from 288 to 320 mm. The irrigation depths for the individual soils resulted in four significantly different groupings or potential management zones. For the Rainfall/ET_o ratio range from 50% to 60%, the irrigation depths for the individual soils ranged from 250 to 293 mm. Theses irrigation depths resulted in four significantly different and distinct groupings (or potential management zones). The Rainfall/ET_o ratio range from 60% to 75% simulations produced irrigation depths ranging from 235 to 283 mm and resulted in five significantly different groupings (or management zones) with some grouping overlap in the soil with higher WHC. For the Rainfall/ET_o ratio greater than 75%, the irrigation depths ranged from 163 to 215 mm and produced five significantly different groupings (or management zones) with some grouping overlap for the soils with lower WHC. In considering the Rainfall/ET_o ratio in the simulations, four to five management zones were identified compared to only two when simulating the entire period. As expected, in years with greater rainfall, irrigation depths were less for all soils. In years with the lowest Rainfall/ET_o ratio, differences in irrigation depths between the soil with the least WHC and the soil with the greatest WHC were lower compared to the years with the higher Rainfall/ET_o ratios. This would correspond to the soil with the lower WHC being depleted more frequently and needing more frequent irrigations. The overall difference in water applications over the 21-year simulation period between soil management zones was approximately 19%. The difference in water applications between soil management zones ranged from 11% to 32% as the Rainfall/ET_o ratio increased due to the increased utilization of rainfall in the soils with greater WHC.

To evaluate the potential water conservation, we utilized the results of simulations of the individual soils to simulate the potential water savings using defined management zones based on soil WHC versus using UI (table 3). The field was simulated using a UI based on the soil type with the greatest field area. For simulations based on management zones, the field was divided into two and four management zones based on the WHC of the soils as previously described. The simulation of the UI produced a mean irrigation application of 263 mm for the entire period. The irrigation application for the lowest to highest rainfall/ET_o ratios ranged from 313 to 206 with greater irrigation being required during the years with the lowest rainfalls.

For the two-management zone simulation, the mean irrigation depths for the soils with the lower WHC was 274 mm and for the higher WHC soils was 250 mm. For the two management zones, the differences in water application depths between management zones ranged from 6% to 14%.

For the four-management zone simulations, the application depths were 274, 266, 257, and 244 mm, respectively, for the lowest WHC zone to the highest WHC zone. The irrigation application depths for the simulations with the Rainfall/ET_o ratios produced differences between the irrigation application depths ranging from 20 to 37.5 mm. Results from

Table 3. Simulated average irrigation requirements for a uniform irrigation with one management zone, two management zones and four management zones for all years and for the years with different levels of Rainfall/ET$_o$ Ratio's using 12.5 mm irrigation applications.

Management Zones	Management Zone	Rainfall/ET$_o$ Ratio <50% Mean	Std Dev	50% to 60% Mean	Std Dev	60% to 75% Mean	Std Dev	>75% Mean	Std Dev	All Years Mean	Std Dev
		Irrigation (mm)									
One	1	313	38	283	31	260	22	206	32	263	51
Two	1	320	35	293	33	283	17	215	34	274	50
	2	303	44	270	33	248	20	192	35	250	54
	Maximum Difference	17		23		35		23		24	
Four	1	320	35	293	33	283	18	215	34	274	51
	2	318	37	283	31	265	22	210	34	266	51
	3	310	44	273	36	253	26	204	31	257	51
	4	300	39	263	38	245	19	181	38	244	56
	Maximum Difference	20		30		38		34		30	

the four-management zone simulations produced differences in irrigation application depths ranging from 7% to 18% between the management zones.

Scenario 2, Refill Soil Profile to Field Capacity

The simulations were repeated with irrigation applications to fill the soil profile to field capacity. The simulation results for the individual soils over the 21-year period produced irrigation amounts greater than in scenario 1; irrigation amounts ranged from 276 to 303 mm (table 4). Irrigating to fill the soil profile resulted in approximately 50% fewer overall irrigation events than using the 12.5 mm application depths in Scenario 1. The simulation results produced only one grouping (or potential management zone) over the 21-year period.

Irrigation depths for Rainfall/ET$_o$ ratios less than 50% ranged from 340 to 350 mm and resulted in one grouping or potential management zone. For the Rainfall/ET$_o$ ratio range from 50% to 60%, the irrigation depths for the individual soils ranged from 285 to 322 mm and resulted in three significantly different and distinct groupings (or potential management zones). The Rainfall/ET$_o$ ratio range from 60% to 75% simulations produced irrigation depths ranging from 277 to 310 mm and resulted in four significantly different groupings (or management zones). For the Rainfall/ET$_o$ ratio greater than 75%, the irrigation depths ranged from 211 to 253 mm and produced four significantly different groupings (or management zones). The overall 21-year difference in water application depths was approximately 10% between soil management zones. The difference in water applications between soil management zones ranged from 5% to 18% as the Rainfall/ET$_o$ ratio increased due to the increased utilization of rainfall in the soils with greater WHC.

Field simulations based on two and four management zones as previously described were compared to UI (table 5). The simulation of the UI produced a mean irrigation application of 295 mm for the entire period. The irrigation application for the lowest to highest rainfall/ET$_o$ ratios ranged from 330 to 232 mm. For the two-management zone simulation, the mean irrigation depths for the soils with the lower WHC was 295 mm and for the higher WHC soils was 286 mm. Differences between the application depths for the two management zones for the rainfall/ET$_o$ ratio ranged from 0 to 25 mm. For the four-management zone simulations, the overall management zone irrigation applications were 305, 295, 286, and 285 mm, respectively for the lowest WHC zone to the highest WHC zone. The irrigation applications for the simulations with the Rainfall/ET$_o$ ratios produced

Table 4. Simulated average irrigation requirements to refill the soil profile to field capacity for the 12 soil maps units for all years and for the years with different levels of Rainfall/ET$_o$ Ratio's.

Soil	Rainfall/ET$_o$ Ratio <50% n[a]	Irrigation (mm) Mean	Std Dev	50% to 60% n	Irrigation (mm) Mean	Std Dev	60% to 75% n	Irrigation (mm) Mean	Std Dev	>75% n	Irrigation (mm) Mean	Std Dev	All Years n	Irrigation (mm) Mean	Std Dev
BnA	15	349 A[b]	47	13	319 AB	28	13	308 A	20	10	247 AB	27	13	303 A	49
Cx	9	339 A	37	8	285 C	31	8	279 D	40	6	211 C	39	7	275 A	59
Dn	10	340 A	51	9	301 BC	36	9	284 BCD	38	7	227 BC	43	9	285 A	58
ErA	10	336 A	49	9	300 BC	35	9	280 BCD	37	7	227 BC	43	9	283 A	56
GoA	9	338 A	42	8	288 C	33	7	278 D	31	6	214 C	42	7	276 A	58
NbA	11	340 A	42	9	296 C	34	9	291 ABCD	26	7	230 ABC	41	9	286 A	53
NcA	14	351 A	41	13	319 AB	29	13	310 A	22	10	252 AB	31	13	305 A	48
NfA	12	341 A	38	11	317 AB	27	11	299 ABC	37	9	247 AB	48	11	298 A	51
NkA	12	333A	37	12	321 A	28	11	291 ABCD	31	9	246 AB	35	11	295 A	47
NoA	13	338 A	54	12	323 A	29	11	301 AB	40	10	253 A	32	11	302 A	50
NrA	14	351 A	41	13	319 AB	29	13	310 A	22	10	252 AB	31	13	305 A	48
Maximum difference		18			38			33			42			30	
Maximum difference%		5%			13%			11%			18%			10%	
No. of significant zones		1			3			4			4			1	

[a] Average number of irrigations per year.

[b] Irrigation depths in a column with a different letter was significantly different at the 95% level.

Table 5. Simulated number of irrigations and irrigation requirements to refill the soil profile to field capacity for a uniform irrigation with one management zone, two management zones and four management zones for all years and for the years with different levels of Rainfall/ET$_o$ Ratio's.

Management Zones	Sub-Management Zone	Rainfall/ET$_o$ Ratio <50% Irrigation N[a]	Mean	Std Dev	50% to 60% Irrigation n	Mean	Std Dev	60% to 75% Irrigation n	Mean	Std Dev	>75% Irrigation n	Mean	Std Dev	All Years Irrigation n	Mean	Std Dev
One	1	13	330	34	12	321	25	12	291	28	10	246	32	12	295	46
Two	1	12	333	34	12	321	25	11	291	28	9	246	32	11	295	46
	2	11	340	38	9	296	31	9	291	24	7	230	38	9	286	52
	Max Difference (mm)		7			25			0			16			9	
Four	1	14	351	38	13	319	27	13	310	20	10	252	29	13	305	47
	2	12	333	35	12	321	26	11	291	28	9	246	33	11	295	46
	3	11	340	42	9	296	34	9	291	26	7	230	41	9	286	53
	4	10	340	47	9	301	33	9	284	35	7	227	40	9	285	57
	Max Difference (mm)		17			25			26			25			20	

[a] Average number of irrigations per year.

similar results with difference between the irrigation applications ranging from 17 and 26 mm.

When considering the field area for the irrigation management zones, the potential overall 21-year irrigation water savings using the soil area-specific calculations resulted in water usages in the two and four management zone simulations of -3.3% and 0.4%, respectively (tables 6 and 7). For the years with the Rainfall/ET$_o$ ratios, the water savings for the two-management zone simulation ranged from -6.8% to 1.1%. Similarly, for the four-management zone simulation the water savings ranged from 1.2% to -5.8%. Individual soils simulations compared to uniform irrigation simulations (table 8 and 9) resulted in an overall water savings of -1.7% to -0.8% and for the years with the different Rainfall/ET$_o$ ratios ranged from -3.4% to 1.4%.

Table 6. Simulated irrigation requirements for different management zones and calculated soil area weighted water savings using 12.5 mm irrigation applications. Water savings calculated based on uniform/one zone irrigation using the soil with the greatest field area.

Management Zones	Sub-Management Zone	Rainfall/ET$_o$ Ratio <50% Irrigation Water Volume (m^3) Mean	50% to 60% Mean	60% to 75% Mean	>75% Mean	All Years Mean
One	1	17786	16078	14797	11737	14941
Two	1	15747	14393	13901	10559	13501
	2	2331	2081	1907	1477	1927
	Total	18078	16474	15808	12036	15429
	Water savings	-1.6%	-2.5%	-6.8%	-2.6%	-3.3%
Four	1	6438	5885	5683	4317	5520
	2	9309	8508	8218	6242	7982
	3	898	790	732	592	745
	4	1442	1262	1176	871	1173
	Total	18,087	16445	15809	12022	15420
	Water savings	-1.7%	-2.3%	-6.8%	-2.4%	-3.2%

Table 7. Simulated irrigation requirements to refill soil profile to field capacity for a uniform irrigation with one management zone, two management zones and four management zones for all years and for the years with different levels of Rainfall/ET$_o$ Ratio's.

Management Zones	Sub-Management Zone	Rainfall/ET$_o$ Ratio <50% Irrigation Water Volume (m^3) Mean	50% to 60% Mean	60% to 75% Mean	>75% Mean	All Years Mean
One	1	18953	18280	16557	14001	16807
Two	1	16388	15805	14315	12105	14532
	2	2618	2278	2242	1773	2206
	Total	19006	18083	16557	13878	16738
	Water Savings	-0.3%	1.1%	0.0%	0.9%	0.4%
Four	1	7,066	6409	6242	5062	6141
	2	9688	9343	8462	7156	8591
	3	985	857	843	667	830
	4	1634	1448	1363	1091	1370
	Total	19373	18057	16910	13976	16932
	Water Savings	-2.2%	1.2%	-2.1%	0.2%	-0.7%

Table 8. Simulated irrigation requirements for different management zones and calculated soil area weighted water savings for each soil type using 12.5 mm irrigation applications.[a]

		Rainfall/ET_o Ratio				All
		<50%	50 to 60%	60 to 75%	>75%	Years
		Irrigation Depth (mm) and Volume (m^3)				
Soil		Mean	Mean	Mean	Mean	Mean
BnA	mm	320	293	283	215	274
	m^3	1026	938	906	688	880
Cx	mm	288	250	238	163	231
	m^3	190	165	157	107	152
Dn	mm	298	263	245	181	244
	m^3	882	778	726	538	722
ErA	mm	300	263	245	181	244
	m^3	167	146	136	101	136
GoA	mm	288	250	235	163	230
	m^3	371	323	304	210	298
NbA	mm	300	268	248	192	249
	m^3	870	775	717	556	721
NcA	mm	320	293	283	215	274
	m^3	3518	3215	3105	2359	3016
NfA	mm	313	278	260	204	261
	m^3	704	625	585	460	587
NkA	mm	313	283	260	206	263
	m^3	7075	6396	5886	4671	5943
NoA	mm	318	283	265	208	266
	m^3	1333	1186	1113	875	1115
NrA	mm	320	293	283	215	274
	m^3	1894	1732	1672	1270	1624
Totals Water	m^3	18028	16278	15307	11833	15193
Uniform Irrigation	mm	313	283	260	206	263
	m^3	17786	16078	14797	11737	14,941
Water Savings		-1.4%	-1.2%	-3.4%	-0.8%	-1.7%

[a] Water savings calculated based on uniform/one zone irrigation using the soil with the greatest field area.

Table 9. Simulated irrigation requirements to refill soil profile to field capacity for different management zones and calculated soil area weighted water savings for each soil type.[a]

		Rainfall/ET_o Ratio				All
		<50%	50 to 60%	60 to 75%	>75%	Years
Soil		Irrigation Depth (mm) and Volume (m^3)				
BnA	mm	349	319	308	247	303
	m^3	1119	1021	987	792	971
Cx	mm	339	285	279	211	275
	m^3	223	188	184	139	181
Dn	mm	340	301	284	227	285
	m^3	223	188	184	139	181
ErA	mm	336	300	280	227	283
	m^3	187	167	156	126	157
GoA	mm	338	288	278	214	276
	m^3	437	372	358	276	357
NbA	mm	340	296	291	230	286
	m^3	437	372	358	276	357
NcA	mm	351	319	310	252	305
	m^3	3861	3502	3410	2766	3355
NfA	mm	341	317	299	247	298
	m^3	768	713	673	557	672
NkA	mm	333	321	291	246	295
	m^3	7540	7271	6586	5569	6686
NoA	mm	338	323	301	253	302
	m^3	1420	1356	1264	1064	1266
NrA	mm	351	319	310	252	305
	m^3	2079	1886	1837	1489	1807
Total Water	m^3	19401	18026	16950	13967	16938
Uniform	mm	333	321	291	246	295
Irrigation	m^3	18953	18280	16557	14001	16807
Water Savings		-2.4%	1.4%	-2.4%	0.2%	-0.8%

[a] Water savings calculated based on uniform/one zone irrigation using the soil with the greatest field area.

In fields with equal size soil areas, the comparison of application depths among management zones may be appropriate and result in potential water savings. However, in this case using actual field soil areas in calculating total water applied resulted in slightly greater water use compared to uniform irrigation management. In previous studies (NiJbroek et al., 2003; King et al., 2006) little to no irrigation water savings were observed. Evans and King (2012) reported that most water savings in VRI could be attributed to turning off water application in specific field areas (wetlands, ditches, etc.) In our simulations, the entire field was assumed to be in crop production and each soil had the same potential productivity, which may not be the case in some soils.

SUMMARY AND CONCLUSIONS

The potential water savings from site-specific variable-rate irrigation (VRI) management was evaluated using soil-specific water balance simulations. The simulations were carried out using a 21-year weather record on a field with 12 soils mapping units that had a 65% difference in water holding capacities. Over the entire 21-year simulation period, the individual soils receiving a 12.5 mm per irrigation produced only two groupings of soils that had significant differences in irrigation water applications depths. Applying irrigation to restore the soil profile to field capacity resulted in fewer irrigations and only 1 grouping or management zone. Averaging irrigation application depths over the entire simulation period masked the impact of weather variability. To address the impact of weather variability, a more in-depth evaluation that was conducted sub-dividing the simulation period into years with different degrees of rainfall/ET_o ratios, resulted in 4 and 5 distinct groupings (or potential management zones) for the 12.5 mm simulations and 1 to 4 groupings with the field capacity irrigations. These simulation results indicate that VRI system design and management should not be solely based on long term average weather conditions but should utilize differing weather conditions when greater irrigation may be required to identify potential management zones for VRI systems. The simulations produced irrigation application depth differences between management zones from 11% to 32% for the 12.5 irrigations and from 5% to 18% for the field capacity irrigations. The greater irrigation application depth differences for the 12.5 mm irrigations were because irrigations only partially refilled the soil profile which required more frequent irrigations. Using these results, two and four management zones were simulated to compare uniform irrigation to spatial VRI applications. For the entire simulation period, the two management zone simulations averaged 0 to 3% less irrigation based on application depth while the four management zone simulations used 3% more to 3% less compared to uniform irrigation. For simulations with different degrees of rainfall/ET_o ratios, the two management zone simulations averaged from 3% more to 8% less irrigation across management zones while the four management zones averaged from 7% more to 8% less irrigation compared to uniform irrigations. However, when the field areas for the individual soils and management zones were accounted for, greater irrigation volumes were calculated for VRI irrigations compared to uniform irrigation. Water usage increased from 1.6% to 6.8% in the 12.5 irrigations and from -1.2% to 2.2% for the field capacity irrigations. Soils with the lowest WHC required irrigation more frequently and had higher irrigation application depths and volumes. These simulation results demonstrate that the large difference in soil water holding capacities in a field may be mitigated by the individual soil areas on the total irrigation volumes required. Both the soil field areas and WHC's should be utilized in developing VRI management zones. For other fields, water usage may vary depending on the soil type properties, variability, and spatial area as well as the soils' productivity potential.

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