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FIELD STUDY OF VARIABLE RATE IRRIGATION MANAGEMENT IN HUMID CLIMATES†

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ABSTRACT

Comparison of variable rate irrigation (VRI) management with uniform rate irrigation (URI) management in soybean and corn crops was studied for 2 years in Stoneville, Mississippi, USA. The experiments were conducted on two 6.7 ha fields. Each of them was equally split into two sectors. VRI management was performed in one sector and URI management in the other. A centre pivot VRI system was used for delivering irrigation water. Soil apparent electrical conductivity (EC) of the fields was used to delineate VRI management zones and create a VRI prescription map. The VRI treatment used 25% less irrigation water and produced 2.8% more yield in soybean and 0.8% more yield in corn than the URI treatment. Irrigation water productivity (WP) of soybean under VRI management was 0.84 kg m^{-3} which is 31.2% higher than URI. The WP of corn under VRI management was 1.69 kg m^{-3}, 27.1% higher than URI. Yield of the rainfed treatment was significantly lower than the VRI and URI treatments for both soybean and corn in the 2015 season ($p < 0.05$). Results in this study demonstrated that VRI management was superior to URI in terms of water use efficiency. Copyright © 2017. This article has been contributed to by US Government employees and their work is in the public domain in the USA.

KEY WORDS: variable rate irrigation; water management; soil electrical conductivity; water productivity

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RÉSUMÉ

L'irrigation à taux variable (VRI) et l'irrigation à taux uniforme (URI) du soja et du maïs ont été étudiées pendant deux ans à Stoneville, Mississippi, États-Unis. Les expériences ont été menées dans deux champs de 6.7 ha. Chacun d'eux a été également divisé en deux secteurs, l'un géré à taux variable, et l'autre à taux uniforme, respectivement. Un pivot central a été utilisé pour fournir de l'eau d'irrigation du système VRI. La conductivité électrique apparente du sol (CE) des champs a été utilisée pour délimiter les zones de gestion VRI et créer une carte de prescription VRI. Le traitement VRI a utilisé 25% de moins d'eau d'irrigation et produit 2.8% de rendement en soja et 0.8% plus de rendement en maïs que le traitement URI. La productivité de l'eau d'irrigation (WP) du soja sous gestion VRI était de 0.84 kg m^{-3}, ce qui est 31.2% plus élevé que l'URI. Le WP du maïs sous gestion VRI était de 1.69 kg m^{-3}, soit 27.1% de plus que l'URI. Le rendement du traitement pluvial était significativement plus faible que les traitements VRI et URI à la fois pour le soja et le maïs en saison 2015 ($p < 0.05$). Les résultats de cette étude ont démontré que la gestion VRI était supérieure à l'URI en termes d'utilisation efficace de l'eau. Copyright © 2017. This article has been contributed to by US Government employees and their work is in the public domain in the USA.

MOTS CLÉS: taux variable d'irrigation; gestion de l'eau; conductivité électrique du sol; productivité de l'eau

INTRODUCTION

Irrigation plays a key role in agricultural production throughout the world. In the United States, irrigated agriculture is a major consumer of fresh water, accounting for 80% of the nation's consumptive water use (Schaible and Aillery, 2015). Irrigation is essential for crop production in arid and semiarid regions. However, in recent years, the acreage of irrigated land has increased rapidly in humid regions, including the Mississippi Delta, one of the major crop production regions in the United States. The main row crops in this region are corn, soybean, and cotton. Though typical

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annual precipitation is about 130 cm in the Mississippi Delta, only about 18% of the precipitation occurs during June to August when the crops require a large quantity of water to grow. Furthermore, the precipitation patterns in summer frequently include heavy rainfall events that increase runoff from cropland with only a small amount of rainfall percolating into the soil profile and available for plant use. Uncertainty in the amount and timing of precipitation is one of the most serious risks to crop production in the Mississippi Delta. Studies have demonstrated that supplemental irrigation in this humid region could increase crop yield and reduce production risk (Cassel *et al.,* 1985; Boquet, 1989; Sui *et al.,* 2014). Producers in this region have become increasingly reliant on supplemental irrigation to ensure adequate yields. In the Mississippi Delta region, approximately 90% of irrigated cropland relies on the groundwater supply from the Mississippi River Valley Alluvial Aquifer. Excessive withdrawal of groundwater has resulted in a decline in aquifer levels across the region. Reports from Yazoo Mississippi Delta Joint Water Management District (YMD) showed that the aquifer level in Sunflower County of the Mississippi Delta dropped 655 cm from 1990 to 2012. In 2015, the level declined 13.7 cm across the Mississippi Delta region. Ongoing depletion and stagnant recharging of the aquifer jeopardize the long-term availability of the aquifer and place irrigated agriculture in the region on an unsustainable path. Local governments, organizations, and producers in the region are realizing the necessity of seeking improved irrigation technologies to increase water use efficiency for sustainable use of water resources.

Soil physical properties in the Mississippi Delta region can vary significantly within a single field from excessively drained loamy sands to poorly drained clays (Cox *et al.,* 2006; Thomasson *et al.,* 2001). It results in differing water storage capabilities and amounts of water available to the crop, contributing to spatial variability of crop growth, and creating challenges in crop water management. Due to within-field soil variability, plants in one location may need more water than those in another location in the field. Treating the plants differently based on their needs is necessary for optimizing water use efficiency.

Variable rate irrigation (VRI) technologies are capable of delivering the desired amount of water to specific locations in the irrigated area, which makes it possible for farmers to address the temporal and spatial variability of the soil and plants within a field. VRI technologies generally include: (i) sensors and spatial information techniques to measure soil and plant growth conditions within a field (O'Shaughnessy *et al.,* 2016; Wang *et al.,* 2013); (ii) algorithms to calculate site-specific water needs based on the measurements, delineate site-specific management zones, and generate VRI prescriptions (Evans and King, 2012); and (iii) devices to control individual sprinklers or groups of sprinklers to deliver the desired amount of irrigation water to each site-specific management zone within the field according to the VRI prescription.

Much research has been done on the use of sensors and the global positioning system (GPS) to gather information on soil and plant conditions, which includes using electrical conductivity sensors to map soil electrical conductivity (EC) (Rhoades *et al.,* 1997; Kitchen *et al.,* 1999; Fraisse *et al.,* 2001; Johnson *et al.,* 2003), soil moisture sensors to measure soil moisture content or soil water potential (Dukes and Scholberg, 2004; Evett and Parkin, 2005; Robinson *et al.,* 2008; Vellidis *et al.,* 2008; Sui and Baggard, 2015), thermal irradiation sensors to detect plant canopy temperature (Jackson, 1986; Cohen *et al.,* 2005; O'Shaughnessy and Evett, 2009; Sui *et al.,* 2012), spectral reflectance and ultrasonic sensors to predict plant health characteristics (Sui *et al.,* 1989; Kostrzewski *et al.,* 2003; Sui and Thomasson, 2006; Detar *et al.,* 2006; Yin *et al.,* 2012, Sui *et al.,* 2013), and mass-flow sensors to map crop yields (Searcy *et al.,* 1989; Grisso *et al.,* 2009; Thomasson and Sui, 2003).

VRI control devices are usually implemented on a centre pivot and linear move sprinkler irrigation systems. Speed control and duty-cycle control are two primary control methods currently used to realize VRI (LaRue and Evans, 2012). The speed control method changes the travel speed of the sprinkler irrigation system to vary the water application depth. As the other operational parameters of the irrigation system remain constant, the higher the travel speed, the lower the water application depth. The speed control method is easy to implement and inexpensive. However, it is only able to vary the application rate in the direction of travel of the irrigation system, not along the lateral pipeline, resulting in difficulty developing randomly shaped VRI management zones to address the variability of soil and plant characteristics across the field. The duty-cycle control method changes the duty cycle of individual sprinklers or groups of sprinklers installed along the lateral pipeline. As the irrigation system moves at a constant speed, the VRI controller adjusts the on/off time of the sprinklers to achieve the desired water application rate. The duty-cycle control method is capable of varying the irrigation rate in the system's direction of travel and along the lateral pipeline, which offers flexibility in development of the management zones (Yang *et al.,* 2015).

VRI research began in the 1990s. Most of the studies on VRI focused on the development of hardware and software systems to site-specifically deliver a certain amount of water to each management zone within a field (Fraisse *et al.,* 1992, 1995a, 1995b; McCann and Stark, 1993; Evans *et al.,* 1996, 2010; Camp *et al.,* 1997; Omary *et al.,* 1997; King *et al.,* 1998; Perry *et al.*, 2003). There have been a very limited number of studies on the development of VRI algorithms and management zones to optimize water use efficiency and farming profits (King *et al.*, 2006; Sadler *et al.*, 2002; Booker *et al.*, 2006). Sprinkler irrigation systems equipped with VRI controllers are now commercially available. The lack of effective methods to create VRI prescriptions using the information from various sensors and the insufficiency of evidence to prove the advantages of VRI practice have become a bottleneck in the development and adoption of VRI technologies.

The objectives of this study were to develop a method for VRI management and evaluate the impact of VRI management on soybean and corn yield and on water productivity in humid climates.

MATERIALS AND METHODS

Experimental site

The study was conducted in 2014 and 2015 in two adjacent fields (Fields A and B) at the USDA-ARS Crop Production Systems Research Unit research farm in Stoneville, Mississippi, USA (latitude: 33° 26′ 30.86″, longitude: 90° 53′ 26.60″). Each field is 6.7 ha with a 1% slope from west to east. Soil samples were taken from Fields A and B in a 0.3-ha grid and 15-cm depth, and analyszed for soil physical properties in 2013. Though silt loam was the predominant soil type, variability in clay and sand content existed across the fields (Table I). Fields A and B were under the coverage of a VRI centre pivot irrigation system, and occupied half of the pivot's full circle between 0 and 180°. Field A was in the circular angle 0–90° while Field B was in 90–180° (Figure 1). In the experimental treatment set-up, each field was divided equally into two sectors, Sector 1 (S1) and Sector 2 (S2) in Field A, and Sector 3 (S3) and Sector 4 (S4) in Field B. Three irrigation treatments were employed in this study: VRI management, uniform rate irrigation (URI) management, and rainfed. In order to compare VRI management with URI management, S2 in Field A and S3 in Field B were assigned to the VRI treatment, and S1 in Field A and S4 in Field B to the URI treatment. The remaining area not covered by the pivot in each field was assigned to the rainfed treatment (Figure 1).

Centre pivot VRI system

The irrigation system consisted of a Valley 8000 standard pivot coupled with the Valley VRI zone control package (Valmont Irrigation, Valley, NE, USA). Field tests showed that this centre pivot VRI system had a coefficient of uniformity of 86.5% with constant rate application, and 84.3% with variable rate application (Sui and Fisher, 2015). The system was configured in four spans with a total length of 233 m. Sprinklers along the length of the centre pivot were divided into 10 control zones, with each zone covering the same surface area of 1.7 ha (Figure 1). The Valley VRI controller included the zone control units, solenoid valves, a GPS receiver, and software. The zone control unit controlled the duty cycle of the sprinklers by turning electric solenoid valves on and off to achieve desired application depths in individual control zones. The GPS receiver determined the pivot's position in the field for identification of control

Table I. Assignment of management zones, irrigation treatments based on soil EC coupled with soil physical property in Fields A and B

Field	Treatment	Management zone	Irrigation rate (%)	EC_{dp} category	EC_{dp} ($mS\ m^{-1}$)	Clay (%)	Silt (%)	Sand (%)
A	VRI	MZ-A	100	1	4.3–41.5	2.03 (1.25–3.75)	71.6 (68.3–79.0)	26.4 (18.5–30.5)
		MZ-B	80	2	41.5–49	2.50 (1.25–7.50)	71.1 (66.5–76.0)	26.4 (16.5–32.3)
		MZ-C	60	3 and 4	49–171	3.59 (1.25–8.75)	75.34 (68.3–79.3)	21.1 (12.0–30.5)
	URI	MZ-A	100	1	4.3–41.5	2.03 (1.25–3.75)	71.6 (68.3–79.0)	26.4 (18.5–30.5)
		MZ-B		2	41.5–49	2.50 (1.25–7.50)	71.1 (66.5–76.0)	26.4 (16.5–32.3)
		MZ-C		3 and 4	49–171	3.59 (1.25–8.75)	75.3 (68.3–79.3)	21.1 (12.0–30.5)
	Rainfed	MZ-A	0	1	4.3–41.5	2.03 (1.25–3.75)	71.6 (68.3–79.0)	26.4 (18.5–30.5)
		MZ-B		2	41.5–49	2.50 (1.25–7.50)	71.1 (66.5–76.0)	26.4 (16.5–32.3)
		MZ-C		3 and 4	49–171	3.59 (1.25–8.75)	75.3 (68.3–79.3)	21.1 (12.0–30.5)
B	VRI	MZ-A	100	1 and 2	4.3–49.	1.50 (1.25–2.5)	71.8 (65.377.8)	26.7 (19.8–33.5)
		MZ-B	80	3	49–57.5	2.50 (1.25–3.75)	67.4 (63.0–70.3)	30.1 (27.3–33.3)
		MZ-C	60	4	57.5–171	2.60 (1.25–7.5)	72.9 (52.5–81.0)	24.5 (15.0–45.0)
	URI	MZ-A	100	1 and 2	4.3–49	1.50 (1.25–2.5)	71.8 (65.3–77.8)	26.7 (19.8–33.5)
		MZ-B		3	49–57.5	2.50 (1.25–3.75)	67.4 (63.0–70.3)	30.1 (27.3–33.3)
		MZ-C		4	57.5–171	2.60 (1.25–7.5)	72.9 (52.5–81.0)	24.5 (15.0–45.0)
	Rainfed	MZ-A	0	1 and 2	4.3–49	1.50 (1.25–2.5)	71.8 (65.3–77.8)	26.7 (19.8–33.5)
		MZ-B		3	49–57.5	2.50 (1.25–3.75)	67.4 (63.0–70.3)	30.1 (27.3–33.3)
		MZ-C		4	57.5–171	2.60 (1.25–7.5)	72.9 (52.5–81.0)	24.5 (15.0–45.0)

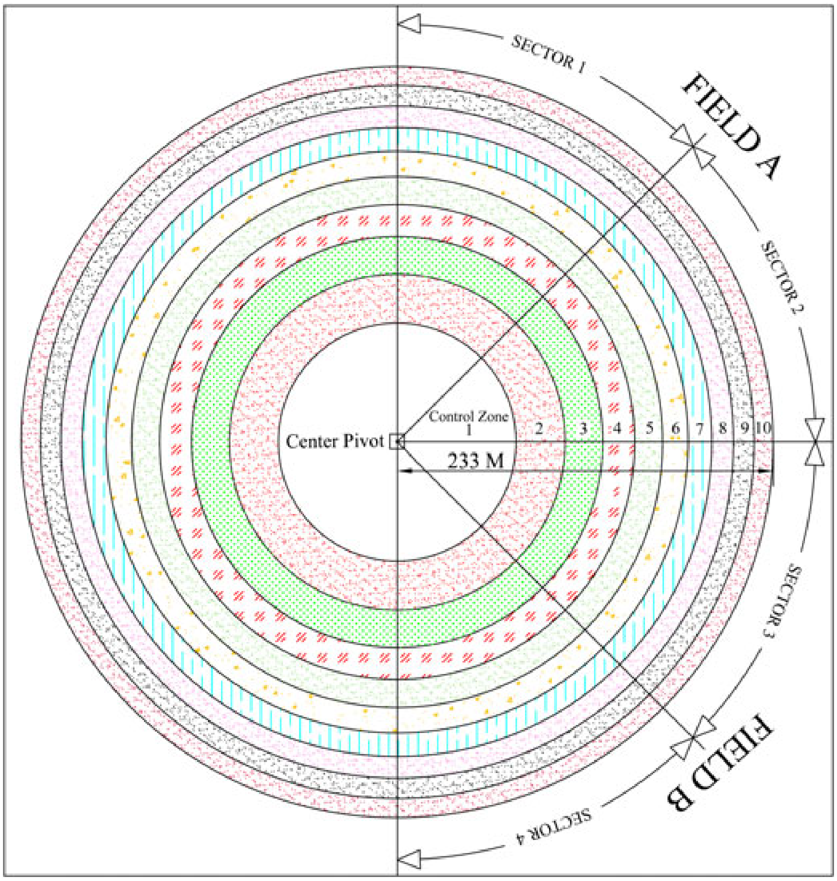

Figure 1. Layout of the experimental fields under coverage of a centre pivot variable rate irrigation system. Sectors 2 and 3 were under the VRI management treatment, sectors 1 and 4 were under the URI management treatment, and the remaining area in Fields A and B were under the rainfed treatment. [Colour figure can be viewed at wileyonlinelibrary.com]

zones in real time. VRI prescriptions were created using the software provided with the VRI system.

Management zone delineation and prescription creation

Many studies on soil EC applications have been reported since the 1980s. These research results demonstrated that soil EC was related to soil properties and crop yield potential, and could be used for site-specific management in precision agriculture (Rhoades *et al.*, 1997; Kitchen *et al.*, 1999; Fraisse *et al.*, 2001; Johnson *et al.*, 2003; Crowin and Lesch, 2003). Veris 3100 soil EC system (Veris Technologies, Salina, Kansas, USA) is one of the devices commercially available and widely adopted for mapping soil EC. This system measures soil EC using the direct contact method. Its soil EC sensor injects a current into the soil through electrodes and measures the voltage that the current generated across the soil. Then the sensor calculates the soil EC using the current and voltage measured. With a GPS receiver, the Veris 3100 system was able to map soil EC at two depths, 0–25 and 0–75 cm, simultaneously. Soil EC in the depth of 0–25 cm was given as shallow EC (EC_{sh}) and in the depth of 0–75 cm as deep EC (EC_{dp}).

In this study, management zones for VRI management were created based on soil EC. Soil EC of Fields A and B was measured in April of 2012 using the Veris 3100 soil EC mapping system described above. EC_{dp} and EC_{sh} were measured simultaneously. The EC_{dp} varied from 4.3 to 141 mS m^{-1}. The EC_{sh} varied from 0.6 to 154 mS m^{-1}, with 50% of the EC_{sh} measurements less than 25 mS m^{-1}. The EC_{dp} was linearly related with the EC_{sh}. With the consideration that more soil water is stored and plant roots grown in the soil horizon of 0–75 cm than in that of 0–25 cm, EC_{dp} was selected for use to delineate VRI management zones. An EC_{dp} map of Fields A and B was created using ArcMap software (version 10.2.1, Esri, CA) (Figure 2). The EC_{dp} was classified into four categories as shown in the map: category 1 from 4.30 to 41.5 mS m^{-1}, category 2 from 41.5 to 49.0 mS m^{-1}, category 3 from 49.0 to 57.5 mS m^{-1}, and category 4 from 57.5 to 171.0 mS m^{-1}. Field A had a larger area of EC_{dp} category 1 than Field B, which contained very

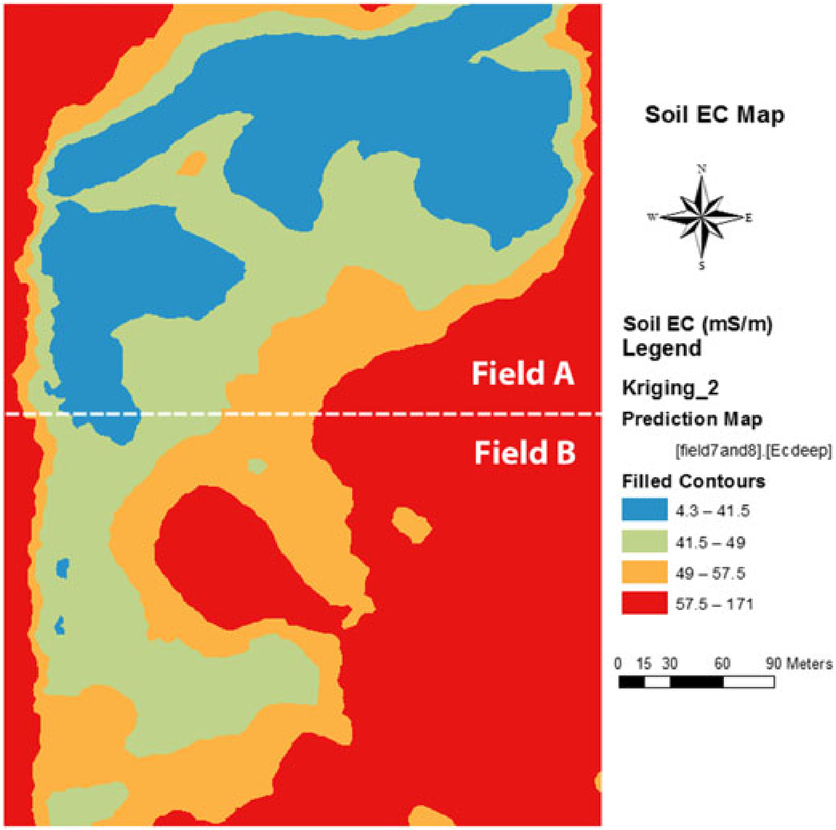

Figure 2. Soil electrical conductivity map of Fields A and B. The filled contours correspond to soil EC_{dp} categories 1–4. [Colour figure can be viewed at wileyonlinelibrary.com]

little category 1. Similarly, the area of EC_{dp} category 4 in Field B was greater than that in Field A.

Although the soil type of the fields was silt loam, deep soil EC varied with soil property. Soil in EC_{dp} category 4 (57.5–171 mS m^{-1}) had the highest clay and lowest sand content (Table I), which contributes to higher water-holding capacity. Soil in category 1 (4.3–41.5 mS m^{-1}) in Field A and category 2 (41.5–49 mS m^{-1}) in Field B shared similar physical properties and had the lowest EC_{dp} in each field respectively (Table I). According to yield maps obtained from previous studies in these two fields, plants in low EC areas generally grew better and yielded more compared with plants in high EC_{dp} areas.

Table I shows the irrigation treatment and management zone assignments. There were three irrigation management treatments: VRI, URI, and rainfed as described in Experimental site (Figure 3). Three management zones were created based on soil EC_{dp}. In Field A, areas in EC_{dp} categories 1 and 2 were assigned as management zones A (MZ-A) and B (MZ-B), respectively. Areas under EC_{dp} categories 3 and 4 were combined to be assigned as management zone C (MZ-C). In Field B, areas in EC_{dp} categories 1 and 2 were merged and assigned as MZ-A, and the areas in categories 3 and 4 were assigned as MZ-B, and MZ-C, respectively.

On account of their soil properties under the EC_{dp} categories and previously observed yield potential, irrigation rates of 100% (R100), 80% (R80), and 60% (R60) were respectively applied to MZ-A, MZ-B, and MZ-C in the VRI treatment. Irrigation rate R100 was applied to the entire URI treatment. No irrigation was applied to the rainfed treatment. Irrigation rate R100 represented the irrigation rate that was determined using soil water content measured by soil moisture sensors, and the application rates of the other management zones were scaled based on their percentages. With the soil EC_{dp} map as the background image, a VRI prescription was generated using software provided by the VRI system manufacturer (Valmont Irrigation, Valley, NE, USA). In the VRI prescription, various depths of irrigation water were applied to different management zones according to the irrigation rate assignments (Figure 3).

Field management

In 2014, soybean was planted in Field A and corn in Field B. In 2015, the crops were rotated, with soybean was planted in Field B and corn in Field A. Soybean varieties P5160LL (Progeny, Wynne, Arkansas, USA) and HBK LL4850 (Bayer CropScience, Research Triangle Park, North

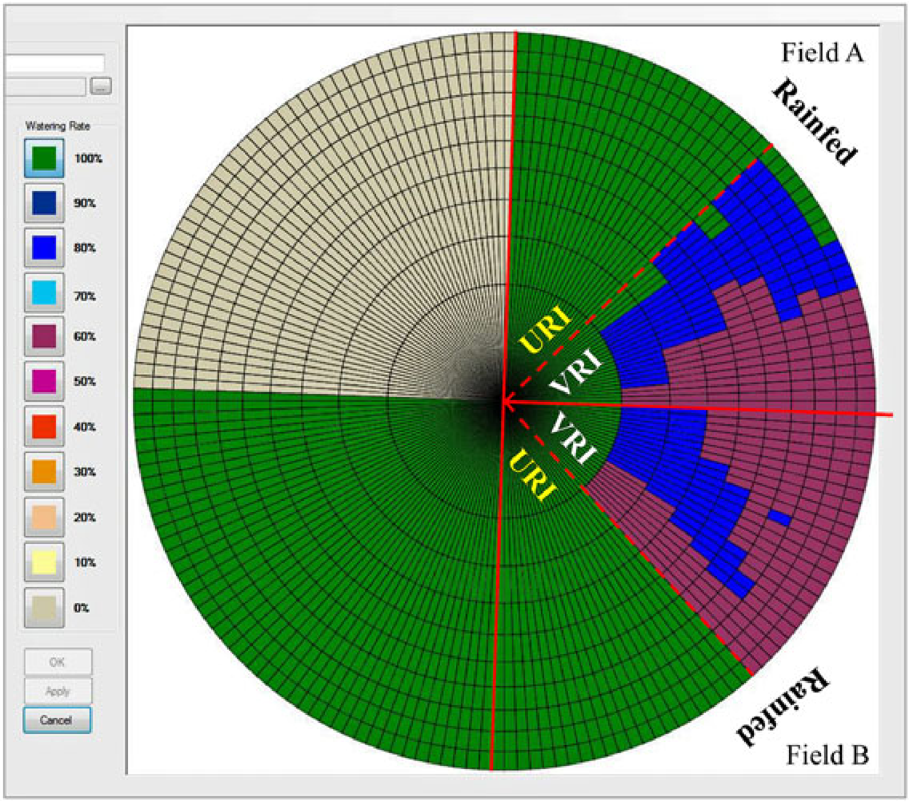

Figure 3. Prescription map for variable rate irrigation in 2014 and 2015. Irrigation water application rates are indicated by different shading on the map. [Colour figure can be viewed at wileyonlinelibrary.com]

Carolina, USA) were selected in 2014 and 2015, respectively. Soybean was planted on 5 May in 2014 and 7 May in 2015. The corn hybrid REV 24BHR93 (Terral Seed, Rayville, Louisiana, USA) was used for both years and planted on 27 March in 2014 and 30 March in 2015. Nitrogen fertilizer at 224 kg ha^{-1} N was applied as a urea-ammonium nitrate solution (N-sol, 32% N) to the cornfield with a side knife drill at 42 days after planting (DAP) in 2014 and 40 DAP in 2015. Insects and weeds in both soybean and cornfields were controlled with generally recommended procedures in the region throughout the growing seasons.

Irrigation scheduling and application

Soil moisture status in each management zone was monitored using a wireless soil moisture sensor network (Sui and Baggard, 2015). For each crop, two locations in each management zone were selected to measure the soil water content. Three soil moisture sensors (EC-5, Decagon Devices, Pullman, Washington, USA) in each location were installed in the soil at depths of 15, 30 and 61 cm. The sensors continuously made one measurement of soil water content every minute and calculated the hourly average of the measurements. The soil moisture data were wirelessly transmitted onto the internet to enable online access for irrigation scheduling. Sensor-measured soil moisture in the 2015 cornfield is shown in Figure 4 as an example. Weighted average of the sensor measurements at three depths was calculated for the soil water content. According to plant root distribution, the weight assigned to the measurement at depths of 15, 30 and 61 cm was 0.45, 0.35 and 0.2, respectively. Irrigation events were scheduled based on the soil water content measured by the sensors. Irrigation was triggered when sensor-measured soil water content dropped close to 74% of field capacity (Figure 4), approximately 50% of plant available water capacity in this case. In each irrigation event, a 2.54 cm depth of water was applied to the R100 zone; water depth applied to the other zones was scaled down according to the rate assigned. Irrigation water was delivered using the centre pivot VRI system described above.

Figures 5 (2014) and 6 (2015) illustrate the rainfall distribution and irrigation events during the crop-growing season between June and August. In 2014, the total amount of precipitation in this period was 39.4 cm. Four irrigation events were scheduled for soybean, with a total water depth of 10.2 cm applied to the R100 zone. Due to

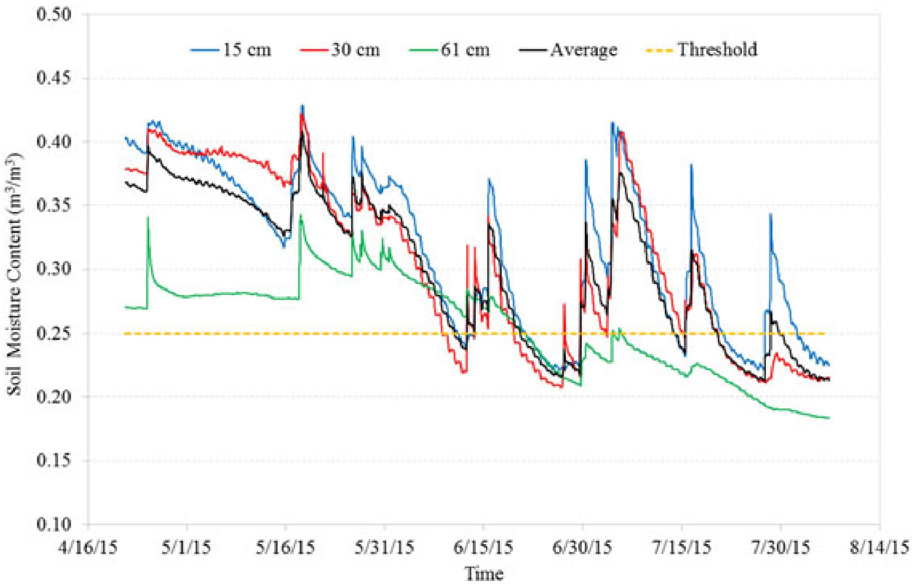

Figure 4. Soil water content variation during the corn growing season in management zone A of the cornfield in 2015. [Colour figure can be viewed at wileyonlinelibrary.com]

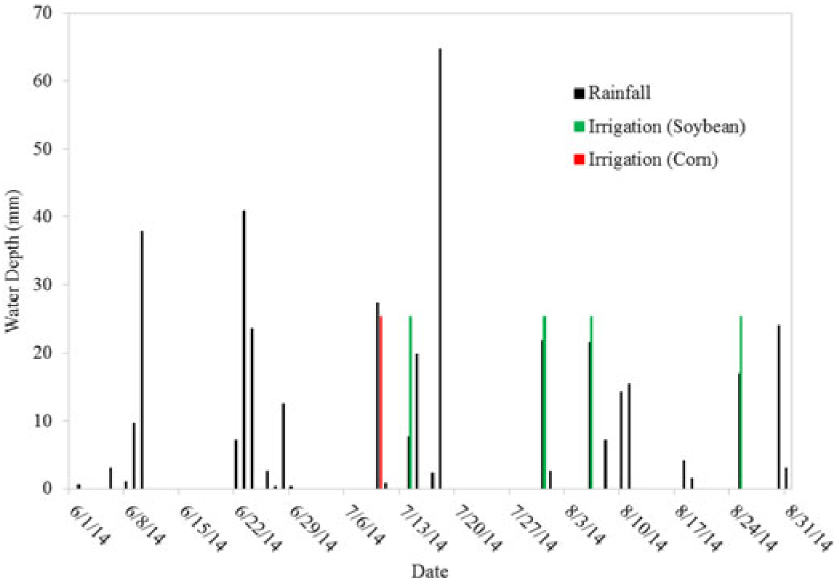

Figure 5. Rainfall distribution and irrigation events in 2014. [Colour figure can be viewed at wileyonlinelibrary.com]

the large amount of rainfall, only one irrigation was conducted for corn with 2.54 cm of water applied to the R100 zone in the VRI treatment, and no irrigation water was applied to the URI treatment in S4. The summer of 2015 was dry in the Mississippi Delta region and the amount of precipitation between June and August was only 14 cm. In the 2015 season, 20.3 cm of irrigation water was applied in eight irrigation events to the R100 zone in soybean, and 17.8 cm of water in seven events to the R100 zone in corn.

Data collection and analysis

The amount of irrigation water used in the VRI and URI treatments was measured using a water flow meter installed at the inlet of the lateral pipeline of the centre pivot. The soybean was harvested on 8 October in 2014 and on 22 September in 2015. The corn was harvested on 10 September in 2014 and on 18 August in 2015. Both were harvested using a combine equipped with a grain yield monitor (AFS Pro 700, Case International) to record the yield data, which

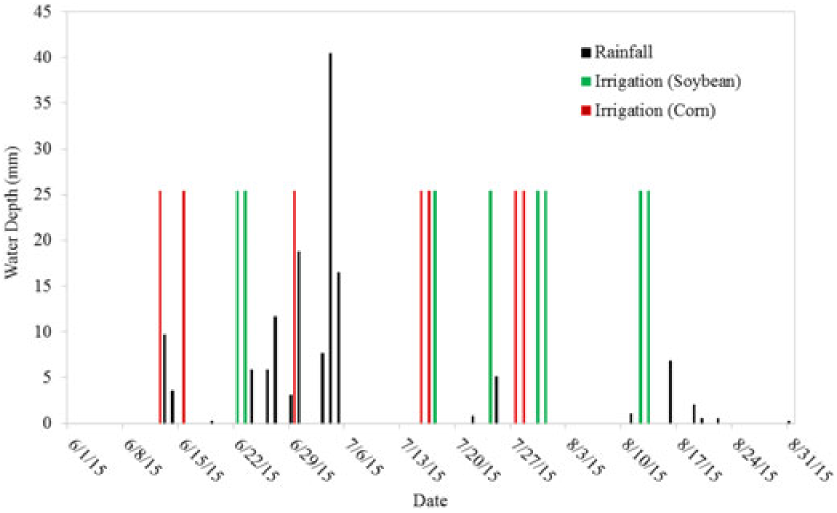

Figure 6. Rainfall distribution and irrigation events in 2015. [Colour figure can be viewed at wileyonlinelibrary.com]

included the latitude and longitude coordinates of each point within the field and the yield associated with that point. The yield data were processed using ArcGIS 10.2.1 software (Esri, Redlands, California, USA) to generate yield maps. In each season, two locations were randomly selected in each management zone of a treatment for yield sampling, which gave 6 yield samples in each treatment, 18 in total for each crop year. In terms of VRI treatment, two yield samples were taken in each irrigation rate. The yield sampling area in each location was approximately 15 × 15 m. Yield values in each sampling area were extracted from the yield map using the ArcGIS software mentioned above, and the average of these yield values was calculated to represent the yield of that sampling location. Mean yield in each management zone within a treatment was calculated.

Yield data from the 18 sampling locations in each crop year were analysed using the PROC GLIMMIX procedure (SAS Institute Inc., Cary, NC) to compare the effect of the irrigation treatment on yield and irrigation water productivity in soybean and corn with the VRI and URI irrigation treatments. Irrigation water productivity (WP) was defined as follows:

$$\mathrm{WP}\left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right) = \frac{\text{Amount of grain produced with irrigation water (kg)}}{\text{Amount of irrigation water used } (\mathrm{m}^3)} \tag{1}$$

RESULTS AND DISCUSSION

Yield in soybean

Table II shows soybean yield with various irrigation treatments and management zones. Soybean yield in 2014 varied from 5465 kg ha^{-1} in MZ-A of the VRI treatment to 3983 kg ha^{-1} in MZ-C of the rainfed treatment. In 2015, the highest yield of 4475 kg ha^{-1} was obtained in MZ-A of the VRI treatment and the lowest yield of 2577 kg ha^{-1} was in MZ-C of the rainfed treatment. For both years, MZ-A of the VRI had the highest yield. The yield distribution within each irrigation treatment followed a similar pattern in that the management zones with lower EC$_{\mathrm{dp}}$ had higher yield. It was quite obvious that soils in MZ-A had a higher yield potential in this case.

Mean soybean yield with different irrigation treatments is shown in Figure 7. In 2014, the mean yield of the

Table II. Soybean yield with various irrigation treatment and management zones in 2014 and 2015 seasons

Year	Irrigation treatment	Management zone	Irrigation rate (%)	Yield* (kg ha^{-1})
2014	VRI	MZ-A	100	5 465^{a}
		MZ-B	80	5 357^{a,b}
		MZ-C	60	4 289^{c}
	URI	MZ-A	100	5 335^{a,b}
		MZ-B	100	5 104^{a,b,c}
		MZ-C	100	5 059^{a,b,c}
	Rainfed	MZ-A	0	4 277^{a,b,c}
		MZ-B	0	4 235^{a,b,c}
		MZ-C	0	3 983^{b,c}
2015	VRI	MZ-A	100	4 475^{a}
		MZ-B	80	4 314^{a}
		MZ-C	60	4 077^{a,b}
	URI	MZ-A	100	4 330^{a}
		MZ-B	100	4 050^{a,b}
		MZ-C	100	3 516^{b}
	Rainfed	MZ-A	NA	NA
		MZ-B	NA	NA
		MZ-C	0	2 577^{c}

*Mean yields in the same year with the same letter are not significantly different at the 0.05 level.

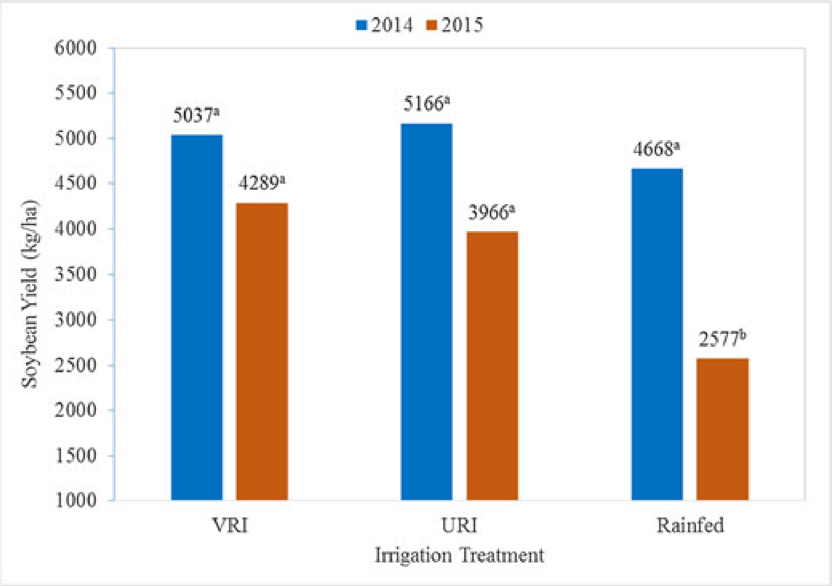

Figure 7. Mean soybean yields with different irrigation treatments in 2014 and 2015. Mean yields in the same year with the same letter are not significantly different at 0.05 level. [Colour figure can be viewed at wileyonlinelibrary.com]

VRI treatment was 5037 kg ha^{-1}, which was slightly lower than the mean yield of 5166 kg ha^{-1} in URI. The mean yield of the rainfed treatment was 369 kg ha^{-1} lower than the VRI treatment and 498 kg ha^{-1} lower than the URI treatment. However, the yield difference between these three treatments was not significant ($p > 0.05$). In 2015, the VRI treatment had the highest yield of 4289 kg ha^{-1}, which was 8.2% higher than the yield in the URI. Yield of the rainfed treatment was 2577 kg ha^{-1}, which is significantly lower than the yields in the VRI and URI treatments. Analysis of the combined 2-yr data showed no significant differences between the yields in VRI and URI. However, the yield of the rainfed treatment differed significantly from that of VRI and URI. Compared with the URI and rainfed treatments, VRI management increased soybean yield by 2.8 and 37.2%, respectively.

However, 2014 was a wet year and the amount of rainfall between the June and August was 39.4 cm (Figure 5). Very limited water stress occurred in soybean plants in 2014 (Figure 5). This could contribute to the small yield difference between the irrigation treatments. The 2015 season was relatively dry and the amount of rainfall between June and August was only 14.0 cm (Figure 6). Irrigation water applied in 2015 was double compared to that in 2014. Results in 2015 showed that VRI management was superior to URI in yield, and the rainfed soybean crops, which experienced water stress, had significantly lower yield than the VRI and URI crops. The impact of irrigation on soybean yield was clearly demonstrated in the 2015 season.

Yield in corn

Corn yields in 2014 and 2015 season are given in Table III. Corn yield in different irrigation treatments ranged from 12 886 to 15 550 kg ha^{-1} in 2014 and from 10 765 to 14 909 kg ha^{-1} in 2015. In 2014, the highest yield was observed in MZ-A of the VRI treatment, while the lowest was in

Table III. Corn yield with various irrigation treatment and management zones in 2014 and 2015 season

Year	Irrigation treatment	Management zone	Irrigation rate (%)	Yield (kg ha^{-1})*
2014	VRI	MZ-A	100	15 550^{a}
		MZ-B	80	13 925^{a,b}
		MZ-C	60	14 049^{a,b}
	URI	MZ-A	0	14 396^{a,b}
		MZ-B	0	13 980^{a,b}
		MZ-C	0	12 886^{b}
	Rainfed	MZ-A	NA	NA
		MZ-B	NA	NA
		MZ-C	0	14 371^{a,b}
2015	VRI	MZ-A	100	13 832^{a,b}
		MZ-B	80	13 978^{a,b}
		MZ-C	60	14 909^{a}
	URI	MZ-A	100	13 728^{a,b}
		MZ-B	100	14 416^{a}
		MZ-C	100	14 232^{a}
	Rainfed	MZ-A	0	13 743^{a,b}
		MZ-B	0	11 423^{b,c}
		MZ-C	0	10 765^{c}

*Mean yields in the same year with the same letter are not significantly different at the 0.05 level.

MZ-C of the URI treatment. In 2015, MZ-C with R60 in the VRI treatment had the highest yield, and the lowest yield occurred in MZ-C of the rainfed treatment. In a wet year such as 2014, MZ-A with low EC_{dp} produced higher yield than the high EC_{dp} zones. Similar results were found in the soybean as well. This illustrated that the soil in the MZ-A zone had high yield potential, and the plants in that zone could yield more if appropriate growth conditions such as adequate soil water were satisfied. The yield results in both soybean and corn supported the irrigation rate assignment of R100 to management zone MZ-A in the VRI prescription. In the dry year of 2015, MZ-C in the VRI treatment produced more corn grain than the other management zones, even under a low irrigation rate of R60. This could be due to the higher clay content of the soil in that EC_{dp} category, which allowed the soil to hold more water for plants to use. The result indicated that assigning a low irrigation rate to a high EC_{dp} zone could be a suitable strategy in writing VRI prescriptions.

Corn yield with different irrigation treatments in 2014 and 2015 is shown in Figure 8. There was no significant yield difference among the irrigation treatments in 2014. Due to the large amount of rainfall, only 2.5 cm water was applied to the VRI treatment in one irrigation event, and there was no irrigation water applied in both the URI and rainfed treatments in corn. Yield in the VRI treatment was 3.2% higher than the average yield of the URI and the rainfed. The only irrigation event during the season was scheduled on 105 DAP. At that time, most of the local corn producers had stopped irrigation for the season. However, results in this study showed that an additional 2.5 cm of irrigation water generated a 3.2% yield increase. Corn yield could be affected by terminating the irrigation too early.

In 2015, the VRI treatment in corn had the highest yield compared to the URI and rainfed treatments. Yield comparison across management zones indicated no difference in VRI and URI treatments. The yield in zone MZ-C of the rainfed treatment was the lowest (Table III). Yield difference between the VRI and URI treatments was not significant. However, yield in both the VRI and URI treatments differed significantly from the yield of the rainfed (Figure 8). Irrigation increased the corn yield by 18%. It demonstrated again that supplemental irrigation in the Mississippi Delta region was necessary and was able to increase the crop yield significantly.

Comparing the yield of soybean and corn in the 2 years, yield of non-irrigated crops was significantly lower than the irrigated crops in the dry year 2015. Though the yield in VRI management was just slightly higher than the yield in the URI, the amount of irrigation water applied with VRI management was 25% less than that applied with URI (Table IV). It was demonstrated in this study that VRI management resulted in water savings. More details regarding water use and water productivity will be described in the next section.

It was found in soybean there was a trend that the zones with lower EC had higher yield (Table II). However, this trend was not very consistent in corn (Table III). It indicates that the relationship between crop yield and soil EC category could vary with crop types. This phenomenon should be taken into consideration as VRI prescriptions are generated using soil EC. Historical crop yield and soil EC data can be used to evaluate the relationship between soil EC and the crop yield.

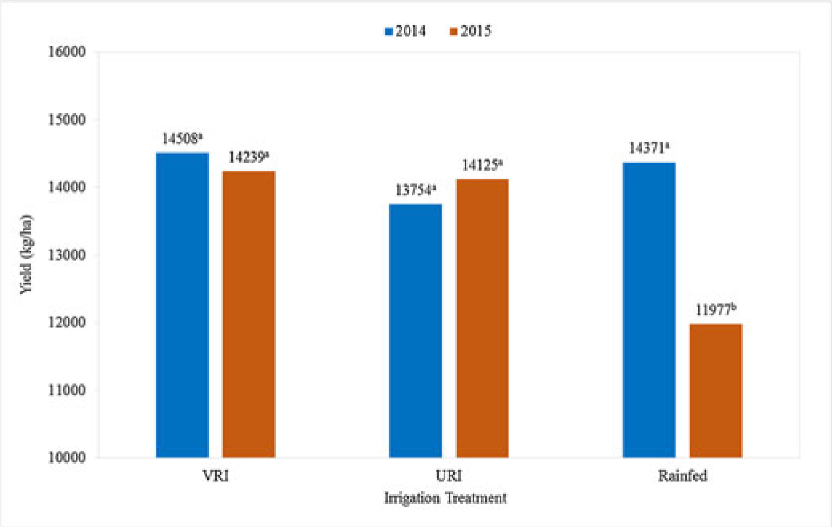

Figure 8. Mean corn yield with different irrigation treatments in 2014 and 2015. Means in the same year with the same letter are not significantly different at the 0.05 level. [Colour figure can be viewed at wileyonlinelibrary.com]

Table IV. Irrigation water amount and irrigation water productivity (WP) of VRI and URI treatment

Crop	Year	VRI water use (m^3)	URI water use (m^3)	VRI water saving (%)	VRI WP ($kg\ m^{-3}$)	URI WP ($kg\ m^{-3}$)
Soybean	2014	1 628	1 965	20.7	0.48	0.54
	2015	3 052	3 965	29.9	1.20	0.75
	Avg.	2 340	2 965	25.3	0.84	0.64
Corn	2014	382	0	NA	2.49	NA
	2015	2 850	3 439	20.7	1.69	1.33
	Avg.	1 616	NA	NA	2.09	NA

Irrigation water productivity

The same VRI prescription was used in the 2014 and 2015 seasons (Figure 3). In soybean, four irrigations were conducted in 2014 and eight in 2015 (Figures 5 and 6). In 2014, corn in the VRI treatment was irrigated once and no irrigation was applied to the URI treatment. In 2015 corn, seven irrigation events were scheduled for the VRI and URI treatments (Figures 5 and 6). The total amount of irrigation water use for each treatment, combined with the irrigation water productivity (WP), is given in Table IV. According to measurements of the water flow meter, water applied to the VRI treatment in sector S2 of Field A and S3 of Field B was 25% less than the URI treatment in sectors S1 of Field A and S4 of Field B in each year (Figures 1 and 3).

Irrigation water productivity (WP) in the VRI and URI treatments was calculated. The WP equals the amount of grain produced by irrigation water divided by the amount of irrigation water applied. In 2014 soybean, the WP in the VRI treatment was slightly lower than the WP in the URI. However, in the 2015 season, the WP in the VRI treatment was 60.1% higher than the WP of URI. In the 2-year averages, the WP in soybean was 0.84 kg m^{-3} in the VRI management and 0.64 kg m^{-3} in the URI. The WP in the VRI was 31.2% higher than that in the URI.

In 2014 corn, the VRI treatment had the highest WP of 2.49 kg m^{-3} because only 2.54 cm irrigation water applied made a 3.2% yield increase. In 2015 corn, the WP in the VRI treatment was 1.69 kg m^{-3}, which was 27.1% greater than the WP in the URI. This result was consistent in soybean, showing the VRI management was able to use irrigation water more efficiently.

CONCLUSION

Soil properties and plant characteristics can vary considerably within a single field, resulting in a variability of water need for plants to reach yield potential. Variable rate irrigation (VRI) technology is able to site-specifically apply irrigation water at variable rates within a single field to account for the temporal and spatial variability in soil and plant characteristics. A field study was conducted for 2 years in a humid region to develop a VRI management method and evaluate the effect of VRI management on crop yield and irrigation water productivity in soybean and corn. Site-specific irrigation management zones were delineated and a VRI prescription was created based on soil apparent electrical conductivity. Irrigation events were scheduled using soil water content measured by soil moisture sensors. Irrigation water was delivered to the site-specific management zones by a centre pivot VRI system according to the prescription. Crop yield and irrigation water productivity in the VRI management were calculated and compared with that in uniform rate irrigation (URI) and rainfed treatments.

There was no significant difference between the yields in the VRI and URI treatments, though yield of the VRI was slightly higher than the URI. However, the amount of irrigation water applied to the VRI treatment was 25% less than the URI treatment. It was obvious in this study that the VRI management resulted in significant water savings. The yield of the rainfed treatment differed significantly from that of the VRI and URI treatments in a dry year (2015). No significant yield difference between the rainfed and irrigated treatments in the 2014 season could be due to the sufficient rainfall during that summer. Irrigation water productivity (WP) in soybean was 0.84 kg m^{-3} in VRI management and 0.64 kg m^{-3} in the URI. The WP in the VRI was 31.2% higher than that in the URI. In 2015 corn, the WP in the VRI was 1.69 kg m^{-3}, which was 27.1% greater than the WP of 1.33 kg m^{-3} in the URI. Results indicated the VRI management was able to use irrigation water more efficiently in the humid region. With a large spatial variability of soil EC in a field and understanding the relationships between soil EC, soil properties, and yield potential of the field, the method reported in this article has the potential to be used in other climates and fields to improve irrigation management. We suggest implementing soil moisture sensors at two places in one field to monitor the soil moisture. The soil moisture sensors could be installed in the management zone with 100% irrigation rate. The soil moisture sensors may require calibration with the soil in which the sensors will be installed. Even though the use of soil apparent electrical conductivity to generate irrigation management zones could be an easy-to-use method in VRI management, research on the algorithms with multiple input variables for delineating VRI management zones and determining VRI application rates are needed because there are many factors affecting crop water requirements for irrigation.

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DISCLAIMER

Mention of a commercial product is solely for the purpose of providing specific information and should not be construed as a product endorsement by the authors or the institutions with which the authors are affiliated.

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