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Deep Tillage and Gypsum Amendments on Fully, Deficit Irrigated, and Dryland Soybean

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ABSTRACT

A major limitation to soybean [*Glycine max* (L.) Merri.] yield is the availability of water for crop production; however, water available for irrigation is declining in many of the crop growing regions. The objectives of this study were to validate and/or refine current allowable deficit recommendation for evapotranspiration (ET)-based irrigation scheduling for furrow irrigated soybean and to examine the effects of deep tillage and gypsum amendment on yields and water use efficiency (WUE). This experiment was conducted near Stuttgart, AR, across three growing seasons on a soil type described as a fine, smectitic, thermic Typic Albagualf. The soil management treatments were deep tillage, deep tillage/gypsum application, conventional tillage/gypsum application, and conventional tillage. Irrigation treatments (fully irrigated, +1 deficit, +2 deficit, and non-irrigated), were replicated three times within each soil treatment. Increases in soybean yields above 20% (2013), 9% (2014), and above 10% (2015), were observed in the deep tillage treatments. No yield benefits were observed in the gypsum amendment treatments. The +1 deficit resulted in reduction of irrigation water used and can be used in conjunction with deep tillage to obtain similar yield responses as fully irrigated treatments. In conventional treatments reduction in yield was observed at all levels of irrigation deficit except for fully irrigated treatments, indicating that conventional soil management practices should follow Arkansas allowable deficit recommendation for ET-based irrigation scheduling as a maximum allowable deficit to prevent yield loss.

Core Ideas

- Deep tillage practices increase soybean yield.
- Irrigation is a recommended practice for maximizing soybean yields.
- As the irrigation deficit is increased the soybean seed yield decreases.

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Crop irrigation is the largest component of human freshwater use (Haddeland et al., 2014). According to Morison et al. (2008), agriculture accounts for 80 to 90% of all freshwater used by humans worldwide.

Soybean is one of the most important leguminous plants in the world. The United States accounts for 38% of global soybean production (Grassini et al., 2015). In 2014, 33,872,623 ha were planted in the United States of which 3.87% was in the state of Arkansas (USDA, 2015a). The average seed yield for the state is 3363 kg ha^{-1} (USDA, 2015a). In Arkansas 82% of the area planted in 2014 was irrigated (USDA, 2015b). However, water available for irrigation is declining in the main growing regions. The increase of irrigated agriculture, climate change, water supply limits, and continued population growth has increased the demand for measures controlling irrigation water usage (Ward and Velazquez, 2008).

The reliance of irrigated crops on ground water has caused many shallow aquifers to decline over the past century by more than 100 m. The projections suggest that by 2050, there will be demand for about 8634 million cubic meters per year of ground water that cannot be met with groundwater supplies in eastern Arkansas (Arkansas Natural Resource Commission, 2014). The general trend in Arkansas's long-term water-level change is that the groundwater levels are declining in response to continued withdrawals at a rate which is not sustainable (Arkansas Natural Resource Commission, 2015). At the same time global populations continue to rise, increasing crop production demand. In turn, soybean production systems face the dilemma of maintaining or increasing yields with less water available to irrigate.

A major limitation to soybean production is the availability of water. The water demand of soybean lies in the range 550 to 800 mm over the course of a growing cycle (Chavarria et al., 2015). Research has shown that water stress is most detrimental to soybean yield during reproductive growth stages (Doss et al., 1974; Sionit and Kramer, 1977; Torrion et al., 2014). Purcell

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Abbreviations: AIS, Arkansas Irrigation Scheduler; ET, evapotranspiration; IUE, irrigation use efficiency; OM, organic matter; WUE, water use efficiency.

and Specht (2004) state that water deficit is the most common abiotic stressor reducing soybean yields. Heatherly and Spurlock (1993) have shown that delays in irrigation initiation, scheduling, and termination can limit soybean yields.

Arkansas soils have very low organic matter (OM) due to the tillage practices and climate. The lack of OM plus the high proportion of silt in Arkansas's silt loam soils (up to 70% silt) increase the propensity for soil sealing (the formation of soil crust), which can significantly affect seedling emergence, but it also impairs the inherent hydraulic conductivity of silt loams. According to Borselli et al. (1996), numerous papers have shown the effectiveness of gypsum additions in reducing crust formation on sodic or generally non-acid soils. Miller (1987), found that gypsum delayed initiation of runoff compared with control, and increased water infiltration. Research by Zandoná et al. (2015), gypsum increased soybean and corn (*Zea mays* L.) yield.

Also due to tillage practices Arkansas soils have high soil compaction levels. Soil compaction is prevalent in soil systems where tillage occurs and can limit yield potential. The presence of a compacted layer in the subsurface is also a factor limiting the soybean yield. Kirnak et al. (2013) has shown that high soil compaction can result in yield losses up to 45%. Compaction influences the hydraulic conductivity and infiltration, soil temperature, and aeration (Borges et al., 2004). Soil compaction is characterized by increased bulk density and soil total porosity and macroporosity reduction (Drescher et al., 2011).

Studies have shown that deep tillage increases water infiltration, internal drainage, and aeration, and thus, increases rooting depth (Strudley et al., 2008). In many sugarcane (*Saccharum officinarum* L.) growing regions deep tillage is thought to be vital to obtaining high crop yields (Yang and Quintero, 1986). A significant amount of time and resources have been devoted to improve WUE to conserve water available for urban and other competing uses, while maintaining high yield potential. Therefore, the optimization of current irrigation and soil management practices is imperative for the sustainability of soybean production systems.

The objectives of this study were to validate and or refine current allowable deficit recommendation for ET-based irrigation scheduling for furrow irrigated soybean and to examine the effects of deep tillage and gypsum amendment on yields and water use efficiency. The results from this study were used to confirm the relevancy of the Arkansas Irrigation Scheduler (AIS).

MATERIALS AND METHODS

The AIS is a computer program developed in the late 1980s and early 1990s and has been used by farmers since that time to schedule irrigation on all crops in Arkansas (Cahoon et al., 1990; Tacker et al., 1996). The scheduler is a computer program that predicts ET using a pan-referenced temperature equation method, crop coefficients calibrated to the region, and soil type and irrigation type based deficits. Deficits change according to crop coefficients referenced to emergence dates. No adjustment is made for soil amendments or other soil treatments such as deep tillage. Earlier unpublished work in 2013 had found that the AIS program and alfalfa (*Medicago sativa* L.) referenced atmometer provided the same irrigation schedule, so atmometers were used in subsequent years for simplicity. For this study the base deficit for furrow irrigated silt loam soil with a pan was adjusted before the crop coefficient was applied for the respective growth stage to determine the irrigation trigger for +1 deficit and +2 deficit irrigation treatments. Fully irrigated treatments followed the current irrigation scheduling recommendations. Thus the study was designed to evaluate the current conventional irrigation recommendations and the interaction of soil treatments (deep tillage, deep tillage with gypsum application, conventional with gypsum application, and conventional alone). The resultant information will be used to validate and, if needed, modify current, recommended, irrigation practices.

The experiment was conducted across three seasons in two locations in Stuttgart, AR (elevation above sea level, 64 m). During 2013 and 2015, it was conducted at Rice Research and Extension Center, University of Arkansas, while in 2014, it was done on a farm field about half a kilometer from the center. "The study area is characterized as being sub-humid and receives 1420 mm per year of precipitation, the majority of which occurs in winter. Summers average 28 degree Celsius in late July to a low of -1 degree Celsius in late December. Wind speeds average 4 m s^{-1} in March to a low of 3 m s^{-1} in August (NOAA, 2011)." At both sites, the experiment was conducted on a soil type classified as Stuttgart soil series or Dewitt silt loam (fine, smectitic, thermic Typic Albagualf) and is composed of a surface layer and subsurface layer characterized as silt loam and presence of silty clay layers in the subsoil (USDA-NRCS, 2005). Formed in alluvium, Dewitt series soils are very deep and poorly drained soils with low permeability (USDA-NRCS, 2005). The soil type is appealing to rice production because the clay horizon has low saturated hydraulic conductivity and impounds water well for flood irrigation. The experimental design is a strip plot design, using large experimental units of 0.2 ha. Two factors, irrigation treatment and soil treatment, were evaluated with four factor levels in each. Four irrigation treatment levels were fully irrigated, dryland, and two deficit treatments (2.54 cm or 1" referred to as plus 1 and a 5 cm or 2" deficit referred to as plus 2). The soil treatment factor levels were conventional tillage, deep tillage, conventional tillage with gypsum amendment, and deep tillage with gypsum amendment. Each factor by treatment had three replications and were randomized.

Plot Design

The field was divided into four blocks, each block received one of the following soil treatments: deep tillage, deep tillage with gypsum application, conventional tillage with gypsum application, and conventional (standard tillage practices in Arkansas). These blocks were further divided into six row plots with 762 mm row spacing, and eight row plots with 762 mm row spacing, for experimental field at Rice Research and Extension Center (2013 and 2015) and farm field (2014), respectively. Irrigation was scheduled by tracking ET losses through the use of an atmometers. The atmometers were fitted with a no. 54 canvas which provided an alfalfa (*Medicago sativa* L.) reference ET estimate (ETgage Company, Loveland, CO). Base deficits have been developed which account for rooting depth, irrigation system type, soil type, and crop type. The base deficit for silt loam with a pan, furrow irrigated soybean is 44 mm, from which crop coefficients are applied based on the growth stage. Thus deficits were reduced as the crop matured. Plots were irrigated with one of four different irrigation treatments (before crop coefficients applied): fully irrigated (Arkansas recommend allowable deficit of 44 mm of irrigation before irrigation), +1 deficit (allowable deficit of 70 mm of ET before irrigation), +2 deficit (95 mm of ET before irrigation), and non-irrigated each having three replicates randomly assigned within each soil treatment block. Note fully irrigated was scheduled in accordance with Arkansas irrigation scheduling using an atmometer (Henry et al., 2015).

Rice Research and Extension Center Site Specifics

2013 and 2015

The study was located in the same field during 2013 and 2015 and was planted with corn in 2014 with the same experimental treatments. The deep tillage consisted of inserting the implement 40-cm deep, 1 m apart on 28 May 2013 and on 5 May 2014 with a five shank no-till soil management system ripper (John Deere; Moline, IL). Plots were planted with soybean cultivar Armor DK 4744 on 29 May 2013 and Progeny 4900 on 6 June 2015 at 65,000 ha^{-1} at 76 cm single row spacings. The soybean emerged 5 June 2013 and 16 June 2015. Gypsum was applied on 4 June 2013 and 6 June 2015 at 2472 kg ha^{-1} using a MagnaSpread 1039 Single Axle Fertilizer Lime Spreader (Katyas Corporation, Cornelia, GA). Cultural practices (fertilizer and weed control) were in accordance with current University of Arkansas' recommendations. These applications were made to the conventional tillage with gypsum amendment and deep tillage with gypsum amendment. Flue Gas Desulfurized gypsum (FSD) was applied soon after planting (Gypsoil, Chicago, IL).The field was harvested on 9 and 11 Oct. 2013, and 13 and 14 Oct. 2015; the middle four rows were harvested for each plot.

Farm Field, Site Specifics

2014

Conventional tillage in rice (*Oryza sativa* L.)–soybean rotations in the mid-South can generally be described as disking of residue, leveling with a "slicker" or land plane to regrade the land from the unevenness created by rice levees. Another land plane operation may also be done to re-level the surface. This results in a very smooth land surface, where field cultivation and "bedder rollers" or beds and furrows are created. Then the crop is planted. In our study we conducted deep tillage before field cultivation and gypsum was applied after bed formation and before planting.

The blocks were deep tilled to a depth of 40 cm at 1 m apart on 23 May 2014, all plots were planted on 24 May 2014. The soybean cultivar was Pioneer P49T97R. The soybean emerged 29 May 2014, and gypsum was applied at a rate of 2472 kg ha^{-1} on 18 June 2014. Plots were harvested on 26 and 27 October. The six middle rows were harvested with a combine, with weights measured using a model GW-150 Grain weigh trailer (Par-Kan Company, Silver Lake, IN). At the time of weighing grain a sample was taken for grain moisture measurements. For each sample (within 24 h) grain moistures were measured, using a model GAC2100 Grain Analysis Computer (Dickey-john Corporation, Auburn, IL).

Cone Penetration Resistance

Cone penetration resistance was measured using a Field Scout Soil Compaction Meter SC900 (Spectrum Technologies inc., Aurora, IL) in the spring of 2014, just prior to tillage. Two cone resistance readings were taken on top of the bed and two in the furrow in four different plots within each soil treatment (Conventional and Deep tillage) block at five different locations down the row (from top to bottom of the field). Readings were taken from the top of the bed and the middle of the furrow at 40 different locations across and down the conventional treatment and 40 across and down the deep tillage treatment block (total of 160 probes with readings occurring 2.5 cm from 0- to 45-cm deep). Average resistance was calculated for each depth across all measuring locations for the readings on the bed and in the furrow.

Water Use, Soil Tension, and Weather Data

Water use was monitored using iron MD30E propeller flowmeters (McCrometer, Hemet, CA). Water use efficiency was calculated by dividing the yield by the amount of water applied both irrigation and total water (rain plus irrigation). The irrigation WUE was determined by dividing grain yield by the amount of irrigation water applied (irrigation use efficiency, IUE) and total WUE by dividing grain yield by total water including rain and irrigation amounts. No adjustment for runoff was made to the rainfall amount. Soil tension was monitored using a 950R (2013) and 975 (2014 and 2015) Irromesh wireless node base data logging systems (Irrometer, Riverside, CA), attached to watermark sensors 200SS (Irrometer, Riverside, CA) placed at three different depths (15.2, 45.7, and 76.2 cm). Temperature sensors were also installed at a depth of 22.9 cm to correct soil tension readings. Weather data was monitored using a H21-001 Hobo data logger equipped with onset sensors as found in U30-NRC weather station starter kit (Onset Computer Corporation, Bourne, MA) located 10 m from the 2013/2015 experimental field.

Root and Shoot Growth and Nodulation

Five plants were collected from each plot during the R3 growth stage. In the field a soil monolith of 40 by 40 by 20 cm (length, width, and depth) was collected containing five plants (shoot plus root), to conduct root, shoot, and nodulation evaluations. The sample was carried to the laboratory where shoots were separated from roots. For each plant, the plant height was measured with a graduated ruler and the number of nodes was counted. The soil was washed from the roots, and nodules were removed from each plant and counted. Lastly the nodules, roots, and shoots of the five plants were dried in forced-air oven at 65°C until a constant mass was obtained (i.e., weighed the same across a 24-h period). Then plant material was weighed using a digital balance and dry mass was recorded.

Canopy Temperature, Canopy minus Air Temperature, Stomatal Conductance

The canopy temperatures were measured with Fluke a Ti25 Thermal Imager (FLUKE Corporation, Everett, WA). Readings were taken at 10 different locations within each fully irrigated and non-irrigated plots across all the soil treatment blocks. Air temperature was recorded at the start and finish of data collection to obtain an average air temperature for the duration data collection. Average canopy temperatures were calculated for each of the treatments. Canopy temperature values were also subtracted from the air temperature at the time of assessment, and values were averaged according to irrigation treatment as well as soil treatment.

Five plants from each plot stomatal conductance were measured using a Leaf Porometer SC-1 (Decagon Devices Inc., Pullman, WA), at the third expanded trifoliate. These measurements were conducted 1 d prior to irrigation (-1 d), during irrigation (0 d), and 3 d after irrigation (3 d) during the R5 growth stage in the 2015 season.

Statistical Analysis

The data was analyzed using SYSTAT 13 software (Systat Software Inc., San Jose, CA). For each year general linear model was used in the form of a two-way ANOVA with the response variable yield (kg ha^{-1}), two factor soil treatment and four factor irrigation treatments (Soil treatment levels: deep tillage, deep tillage + gypsum, conventional tillage + gypsum, and conventional tillage. Irrigation treatments: fully irrigated, +1 deficit, +2 deficit, and non-irrigated). In 2015 the same analysis was also conducted with each of the following response variables, plant height (PH), nodes by soybean plants (N), shoot dry mass (SDM), root dry mass (RDM), nodules by soybean plants, nodules dry mass (NDM) in R3 growth stage. Harvest weights were corrected with a 12% moisture correction, using the measure grain moisture from each plot. The measured outcomes were tested by the assumptions of the mathematical model (normality and homogeneity of variance). The 2014 yield data violated the normality assumption and a Box cox power transformation was performed with a lambda of 4. In the results, significant groupings were based off transformed data analysis however the actual data means were reported. The factor means for each response variable, when significant, were compared by Tukey's test ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Cone Penetration Resistance

The soil penetration resistance is used as an indicator of the degree of soil compaction (Beulter and Centurion, 2004). According to the soil penetration resistance readings, the deep tillage treatments had less resistance compared to the conventional treatment indicating that deep tillage had a positive effect on compaction (Fig. 1A and 1B). Soil compaction is associated with increases in soil density and penetration resistance, as well as reduction in soil macroporosity and total soil porosity (Valadão et al., 2015). Ramos et al. (2015) suggests that the critical level of soil penetration resistance is 2.0 MPa. According to the soil penetration resistance readings in this study, higher resistance, greater than 2 MPa, was recorded at a depth of 7 to 15 cm, indicating the presence of a compaction layer in the conventional treatments (Fig. 1A and 1B). This critical resistance was not observed in the deep tillage treatments indicating the compaction layer was disrupted in this soil management system and that the effects of deep tillage persisted for more than one season.

The soil penetration resistance values were lower on the bed (Fig. 1A) than in the furrow (Fig. 1B). This was expected because the deep tillage shank passes were on the center of the bed.

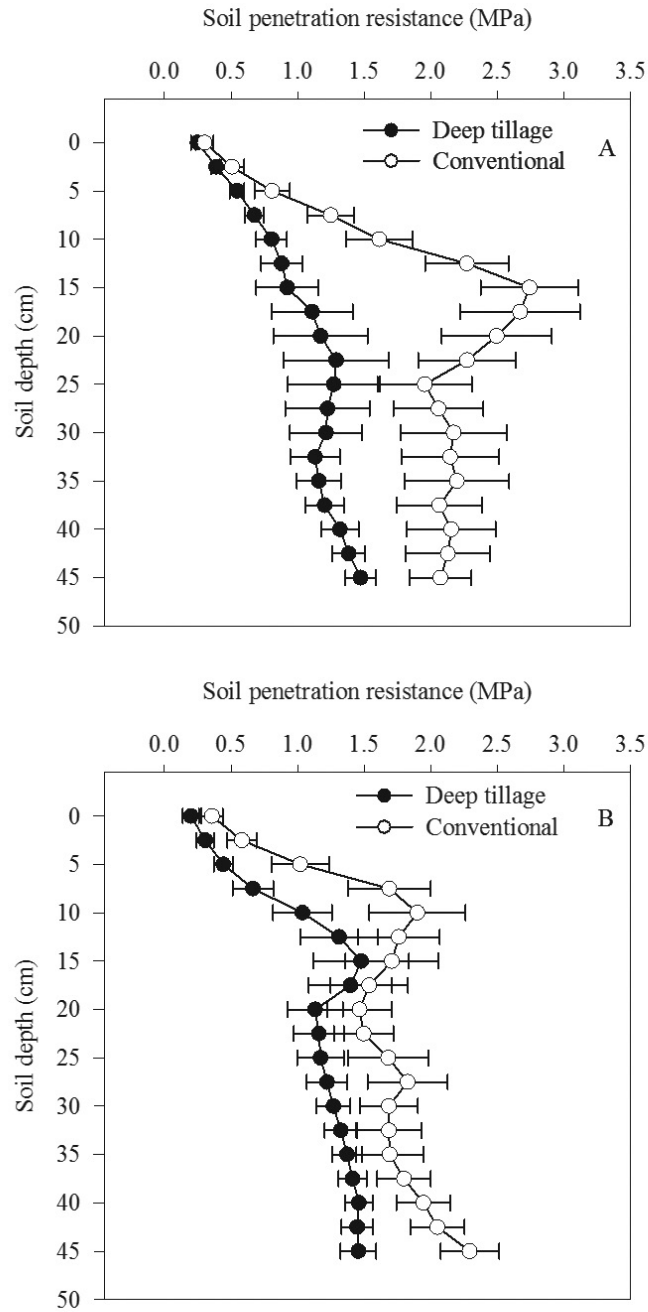

Fig. 1. Average soil penetration resistance (MPa) (A) bed and (B) furrow carried after harvest. Stuttgart, 2015. Error bars indicate two standard errors around the mean of measured values or 95% confidence interval.

The compaction observed in the conventional treatments as well as increased levels of soil penetration resistance in the furrows across treatments, could potentially have an effect on soil air and water holding capabilities as well as plant growth. Compaction can affect the soil-air-water relationship, limiting root growth and development (Cardoso et al., 2006), which may compromise yield potential.

Water Use, Rainfall, and Water Use Efficiency

During the 2013 season, the fully irrigated treatments received 278 mm of irrigation and the +1 deficit and +2 deficit treatments received 73 to 82 mm less, respectively (Table 1). The fully irrigated treatment required six irrigations, two and

Table 1. Irrigation date, number of irrigation (NI), irrigation depth (ID), total irrigation water applied (IWA), total water applied, irrigation plus rain (TWA), irrigation use efficiency (IUE), total water use efficiency (WUE) to 2013, 2014, and 2015 season; Stuttgart, AR, 2015.

Treatment	Irrigation date	NI/ID	IWA	TWA	IUE	WUE
	2013 season	———	mm	———	—— kg mm^{-1}	——
Fully irrigated	5 July, 15 July, 29 July, 8 Aug., 27 Aug., 5 Sept.	06/46	278	463	13.4	8.0
+1 deficit	11 July, 1Aug., 23 Aug., 6 Sept.	04/51	205	390	15.7	8.3
+2 Deficit	12 July, 7 Aug., 30 Aug.	03/65	196	381	15.2	7.8
Non-irrigated	–	–	–	185	–	5.9
	2014 season					
Fully irrigated	11 July, 28 July, 26 Aug.	03/55	166	483	29.4	10.1
+1 deficit	25 July, 27 Aug.	02/69	138	455	35.1	10.6
+2 Deficit	4 Aug.	01/61	61	378	75.3	12.2
Non-irrigated	–	–	–	317	–	12.3
	2015 season					
Fully irrigated	17 July, 24 July, 31 July, 10 Aug., 18 Aug., 4 Sept., 11 Sept.	07/65	457	616	8.2	6.1
+1 deficit	21 July, 3 Aug., 13 Aug., 8 Sept.	04/64	257	416	12.0	7.4
+2 Deficit	24 July, 10 Aug., 10 Sept.	03/67	201	360	14.7	8.2
Non-irrigated	–	–	–	159	–	9.2

three less irrigations were required for the +1 deficit and +2 deficit treatments, respectively (Table 1).

In the 2014 season the fully irrigated treatments received 166 mm of irrigation and the +1 deficit and +2 deficit treatments received 28 to 105 mm less, respectively (Table 1). The water applied in 2014 was lower than that of 2013 as a result of a higher amount of rainfall during the 2014 growing period (78, 69, and 53% higher in June, July, and August, respectively) (Fig. 2A and 2B). In 2014 three irrigations were applied to the fully irrigated treatment, 1 and 2 less irrigations were applied to the +1 deficit and +2 deficit treatments, respectively (Table 1).

The 2015 season was similar to the 2013 growing season, however a little drier (Fig. 2C). In this season the total water applied to the fully irrigated treatment was 457 mm of irrigation and the +1 deficit and +2 deficit treatments received 200 to 256 mm less, respectively (Table 1). The fully irrigated treatment required seven irrigations, three and four less irrigations were required for the +1 deficit and +2 deficit treatments, respectively (Table 1).

Water use efficiency was determined for both IUE, using only the irrigation water applied and total WUE which included rainfall and irrigation contributions. Generally IWE was highest for the +2 deficit and decreased for +1 and fully irrigated. However this was not true in 2013 where IUE was nearly the same (15.2 Kg mm^{-1}for +2 deficit and 15.7 Kg mm^{-1} for +1 deficit). In 2014 the IUE are about double what was found for 2013 and 2015. 2014 was an excessively wet season as evidenced by the low irrigation amount applied (one to three compared to three to seven irrigations).

When accounting for rainfall and irrigation, WUE showed similar trends in 2014 and 2015, where WUE in 2014 was 12.3 Kg mm^{-1}and decreased to 10.1 Kg mm^{-1}for fully irrigated, a similar trend was present in 2015 where WUE was 6.1 Kg mm^{-1}and increased to 9.2 Kg mm^{-1} for dryland. This was an expected result. However for 2013, the trend is reversed, that is the +1 deficit is the most efficient at 8.3 Kg mm^{-1}, followed by the fully irrigated of 8.0 Kg mm^{-1}and +2 at 7.8 Kg mm^{-1}. The dryland in this year was the most inefficient at 5.9 Kg mm^{-1}. Many of the irrigations for the irrigated treatment occurred in August when the pods were developing and filling (R4–R6) and this may explain the low WUE of the dryland and why there was little difference in the WUE of the irrigated treatments. Also, the target irrigation amount for the study was near 63 mm and for the fully irrigated treatment in 2013 the average application depth was 46 mm for the fully irrigated and 51 mm for the +1 deficit. Also the total irrigate applied for the +1 and +2 deficit is only about 9 mm, so while there is an extra irrigation difference between these treatments, the total volume was very similar.

The WUE trends in 2014 and 2015 show that as water becomes more limited WUE improves. Water use efficiency was nearly twice as much in 2014 (10.1–12.3 Kg mm$^{-1)}$ as in 2015 and 2013 (5.9–9.2 Kg mm^{-1}) because much less irrigation was required. These results show that climate and irrigation application amounts and frequency have a substantial influence on IUE and WUE in the mid-South.

Root and Shoot Growth and Nodulation

2015 Season

There were no interaction effects observed between soil and irrigation treatments with respect to plant height, nodes per plant, shoot dry mass, root dry mass, nodules per plant, and nodules' dry mass (Table 2).

Larger plant height measurements and more nodes per plant were observed in the deep tillage treatment. Gypsum amendment in conjunction with deep tillage and conventional systems seemed to have no effect on plant height and little to no effect on nodes per plant. No significant differences were observed in shoot dry mass and root dry mass with respects to soil treatment. More nodules per plant were observed in the conventional and deep tillage with gypsum treatments, likewise higher nodule dry mass per plant were observed in these treatments. However, the results are a little convoluted making it difficult to make clear conclusions on the combination of deep tillage and gypsum, deep tillage, as well as gypsum amendments, treatment effects on nodulation (Table 2).

The largest negative effect of all variables in Table 2 was seen in the non-irrigated treatment. Plants grown in the fully irrigated treatment had more nodules, nodule dry mass, and shoot dry mass. No significant difference was found in plant height, nodes per plant, and root dry mass between fully

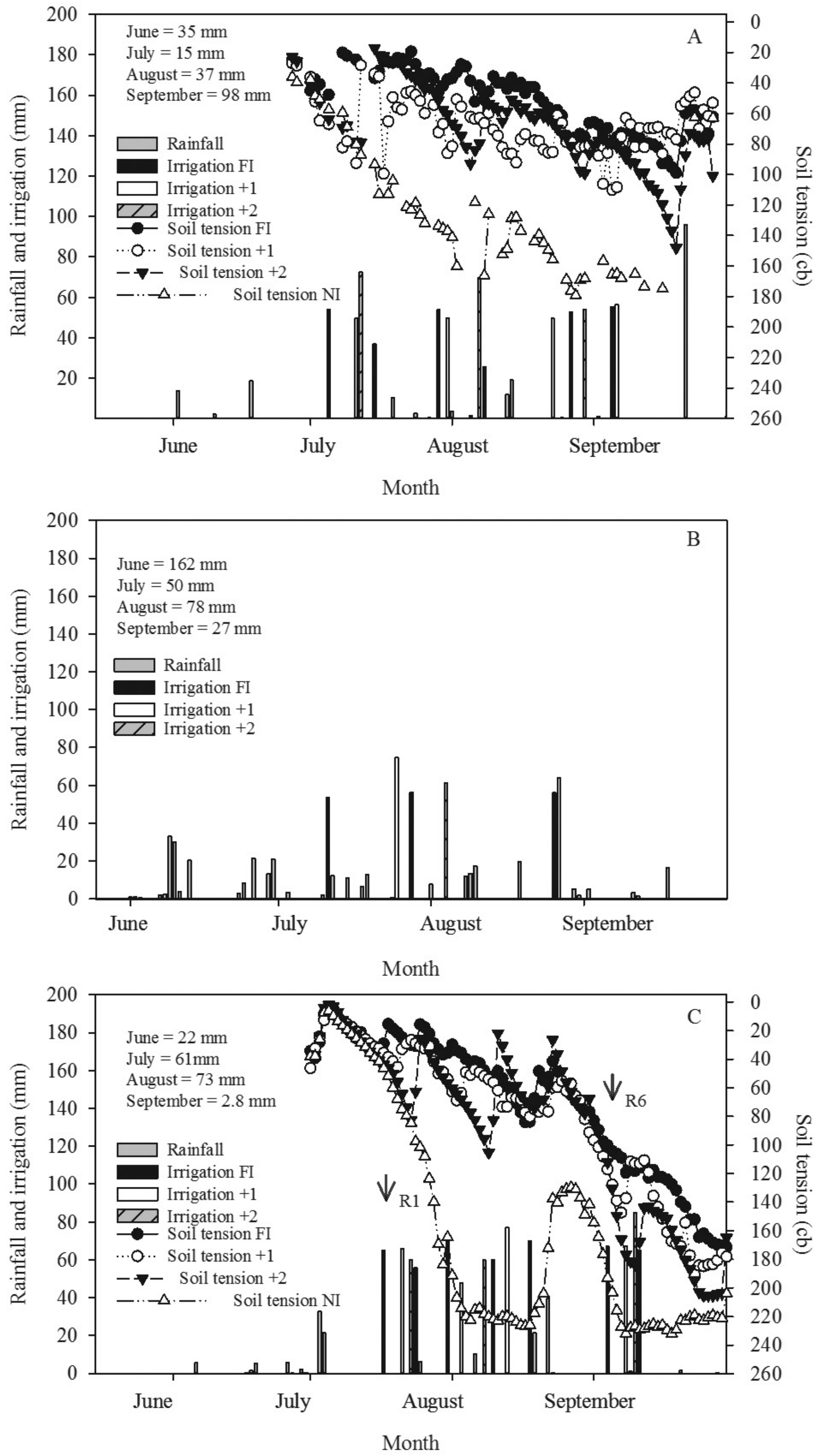

Fig. 2. Rainfall, irrigation and average soil tension across the three depths monitored for the (A) 2013 season, (B) 2014 season, and (C) 2015 season; Stuttgart, AR, 2015. FI = Fully irrigated; NI = non-irrigated. R1 and R6 growth stage according Fehr and Caviness (1977). 2014 season equipment soil tension failed.

irrigated, +1 deficit, and +2 deficit treatment groups. However, when looking at just the irrigated treatments the data suggests: no difference exists in root dry matter between irrigated treatments, no difference in plant height and nodes per plant exists between fully irrigated and +1 deficit and as irrigation deficit increased reductions were observed, shoot dry mass, nodules per plant, and nodule dry mass (Table 2).

A decrease in photosynthetic rate may be related to diffusive factors (stomatal) or metabolic factors (non-stomatal) when a water deficit develops in the field more slowly causing damage

Table 2. Plant height (PH), nodes by soybean plants (N), shoot dry mass (SDM), root dry mass (RDM), nodules by soybean plants, nodules dry mass (NDM) in R3 growth stage. 2015 season; Stuttgart, AR, 2015.

Soil treatment	PH	Nodes	SDM	RDM	Nodules	NDM
	cm	plant^{-1}	——— g plant^{-1}	———		mg plant^{-1}
Deep tillage (DT)	68.5a*	16.4a	15.5a	2.7a	34.2b	173.2b
DT + gypsum (G)	67.5ab	16.3ab	15.5a	2.6a	46.5ab	271.4a
Conventional + G	63.8ab	15.7b	15.5a	2.6a	45.0b	244.1ab
Conventional	58.6b	16.0ab	16.7a	2.9a	58.1a	288.3a
Irrigation treatment						
Fully irrigated	69.8a	17.0a	18.9a	2.7ab	64.4a	335.6a
+1 deficit	69.2a	16.5a	17.5ab	3.0a	51.6ab	267.5ab
+2 Deficit	66.8a	16.3a	15.2b	2.8a	41.8b	237.7b
Non-irrigated	52.6b	14.6b	11.7c	2.3b	26.0c	136.2c
Mean	64.6	16.1	15.8	2.7	45.9	244.2
CV, %	12.9	3.8	14.4	15.7	25.6	35.5

* Means not followed by the same letter in the column differ by Tukey's test at 5% probability.

to soybean vegetative growth (Chavarria et al., 2015). Therefore the plants in the +1 deficit and +2 deficit and non- irrigated treatments may have experienced varying photosynthetic rates as a direct effect of the irrigation treatment. The reduction in plant growth (plant height, nodes by plants, shoot dry mass) observed in the non-irrigated treatment was likely associated with a reduction in photosynthetic reactions as a result of diffusive factors (stomatal) due to water stress. According to Chaves and Oliveira (2004), a moderate water stress applied to soybean caused a decrease in photosynthesis due to a decrease in CO_2 diffusion from the atmosphere to the carboxylation site, as a result of stomatal closing to reduce water loss. Furthermore water stressed conditions cause an imbalance between the capture of energy and metabolism, which result in decreases in photochemical reaction and increased energy dissipation (Lawlor and Tezara, 2009). Also, water stress influences plant nutrition and the establishment of plant organs and function (Prudent et al., 2015).

In this study when comparing fully irrigated to +1 deficit, +2 deficit, and non-irrigated treatments, a reduction in the number of nodules per plant was observed 20, 35, and 60%, respectively. Similarly, Prudent et al. (2015) showed that water stress conditions drastically reduced the number of nodules produced by ~55% at harvest. King and Purcell (2001) also found that water stress can inhibit nodule formation as well as symbiotic N_2 fixation, by decreasing nodule size and by reducing nodule-specific activity. Water stress contributes to a decrease in N_2 fixation and consequently to decreases in photosynthetic rates (Chavarria et al., 2015). Furthermore symbiotic N_2 fixation, has been shown to be the metabolic process most susceptible to water stress in soybean plants (King et al., 2014). Therefore one may speculate that as irrigation deficit was increased in this study reductions in levels of N_2 fixation across irrigation treatments may have occurred. The possible reduction in the metabolic N_2 fixation (non-stomatal) across the irrigation treatments may have contributed to reductions in photosynthetic rates as well. Therefore reduction in plant growth associated with water stress in this study is likely to be a result of a reduction in photosynthetic rate from both diffusive factors (stomatal) and reduction in the metabolic N_2 fixation (non-stomatal).

Effects of Irrigation on Canopy Temperature, Canopy Minus Air Temperature, Stomatal Conductance

2015 Season

Comparison between fully irrigated and non-irrigated treatment were made to evaluate the effect of irrigation treatment on canopy temperature, stomatal conductance, and canopy air temperature difference 1 d prior to irrigation event (-1 d), during an irrigation event (0 d), and 3 d after irrigation (3 d).

As one would expect, the data indicates that plants in the fully irrigated treatments experienced less water stress than the non-irrigated plots. Lower canopy temperatures, lower differences between canopy and air temperature and higher stomatal conductance were observed in the full irrigated plots relative to the non-irrigated plots (Fig. 3A, 3B, and 3C, respectively). In the non-irrigated plots, an average 2°C temperature increase was recorded relative to the fully irrigated treatment pre- and post-irrigation event (Fig. 3A). Irrigation shows to have reduced the difference between canopy and air temperature. Canopy to air temperature difference for the fully irrigated treatment was on average ~4°C lower than the non-irrigated treatments pre- and post-irrigation event (Fig. 3B). Stomatal conductance difference for the fully irrigated treatment was 0.44 mmol m^{-2} s^{-1} higher than non-irrigated treatment pre-irrigation and 0.32 post-irrigation (Fig. 3C).

Effects of Soil Treatments on Canopy Temperature, Canopy Minus Air Temperature, Stomatal Conductance

One day before irrigation (-1) the deep tillage and deep tillage + gypsum treatment showed lower canopy temperature, about 1°C less than the conventional and conventional + gypsum (Fig. 3D) ($p = 0.0011$). About a 0.5°C decrease in this difference was observed after an irrigation event ($p = 0.0289$). Furthermore, the canopy to air temperature difference in the deep tillage and deep tillage + gypsum treatments was ~2°C lower before ($p = 0.0012$) and 1°C lower after irrigation ($p = 0.0297$)., than the conventional and conventional + gypsum (Fig. 3E). The reduction in differences, between treatments with deep tillage and treatments without deep tillage, in both canopy temperatures and the canopy to air temperature difference indicate that the irrigation effect on canopy

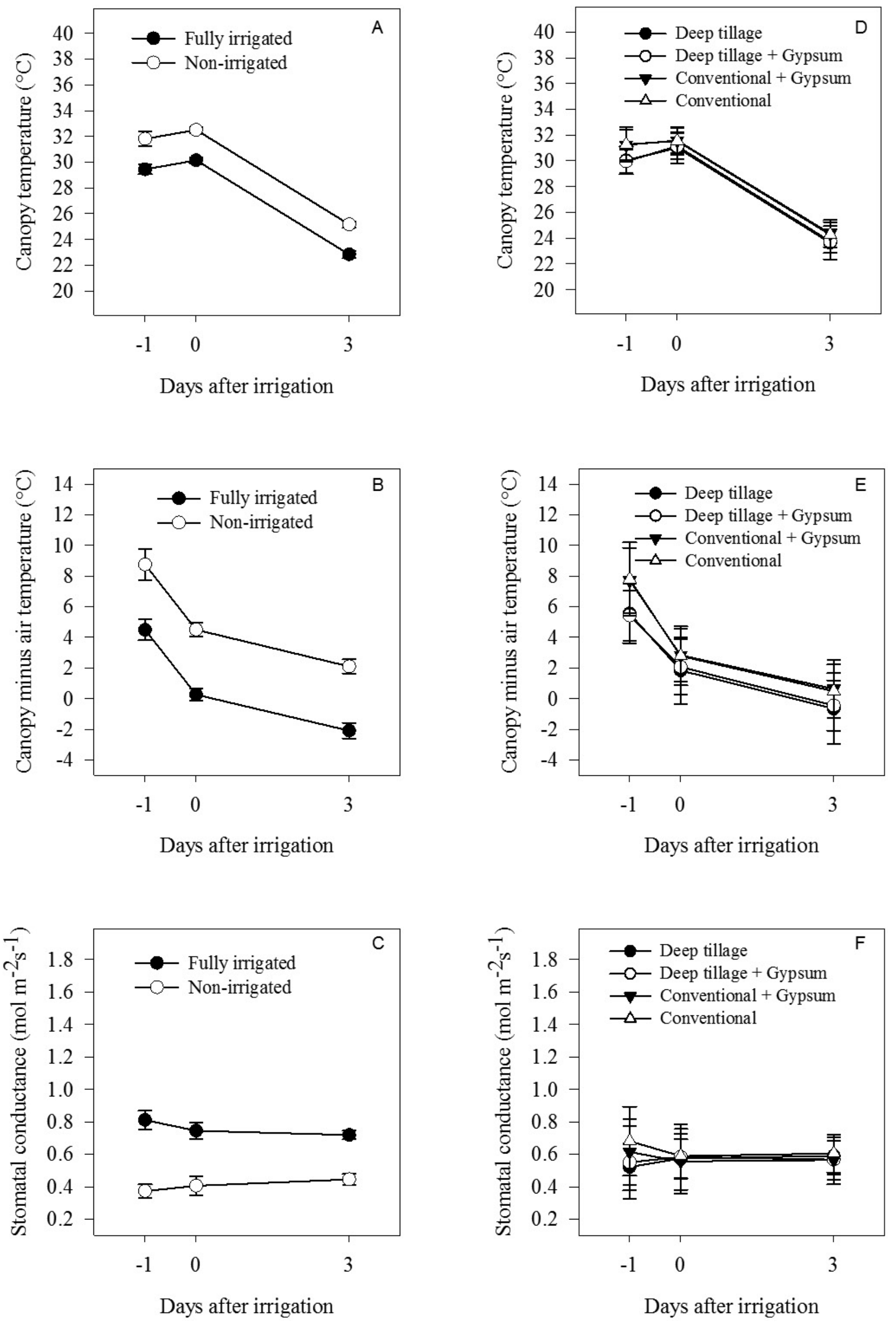

Fig. 3. (A) Canopy temperature, (B) canopy minus air temperature, (C) stomatal conductance to the irrigation and soil treatment, in R5 growth stage according Fehr and Caviness (1977). 2015 season; Stuttgart, AR, 2015. Error bars indicate two standard errors around the mean of measured values or 95% confidence interval.

temperatures minimized the soil treatment effect on canopy temperatures. No soil treatment effect on level of stomatal conductance was observed post- irrigation (Fig. 3F).

Solar radiation absorption causes canopy temperatures to increases; however when the solar energy is used for water evaporation through the stomata, the surface of the leaf is cooled (Dejonge et al., 2015). Under water stress-free conditions, the water transpired by plants evaporates and cools the leaves; in water-stressed conditions, transpiration and subsequent evaporation is restricted causing leaf temperature increases (González-Dugo et al., 2006). In this study, plants in the fully irrigated treatment had a lower canopy temperature than those in the non-irrigated treatment, which indicates that plants in the non-irrigated treatment experience higher levels of water stress. The higher canopy temperatures observed from plants in the non-irrigated treatment was likely due to reduction in transpiration and evaporation through the leaf in response to water stress. Water-stressed plants will reduce transpiration as a result restricting evaporation at the surface of the leaf, which will typically cause higher canopy temperatures relative to non-stressed plants (Throssell et al., 1987; González-Dugo et al., 2006; Dejonge et al., 2015).

The difference between canopy and air temperature, has often been used to quantify water stress (Throssell et al., 1987; DeJonge et al., 2015). Higher differences between canopy temperatures and air temperature indicate higher levels of water stress (Throssell et al., 1987; González-Dugo et al., 2006; DeJonge et al., 2015). Plants in the non-irrigated treatment

Table 3. Seeds yield to the irrigation and soil treatment. 2013 and 2015 season; Stuttgart, AR, 2015.

Soil treatment	Irrigation treatment			
	Fully irrigated	+1 deficit	+2 deficit	Non-irrigated
	Seeds yield			
	2013 season			
	kg ha^{-1}			
Deep tillage	4100.3Aa*	3886.3ABa	3585.6Ba	1277.0Cab
Deep tillage + gypsum (G)	4078.0Aa	3841.3Aa	3641.6Aa	1409.0Ba
Conventional + G	3507.6Ab	2560.3Bb	2201.3Bb	738.6Cc
Conventional	3202.0Ab	2620.3Bb	2478.0Bb	920.0Cbc
Mean	2752.9			
CV, %	7.3			
	2015 season			
Deep tillage	3897.3Aa*	3357.0Ba	3262.3Ba	1656.3Ca
Deep tillage + gypsum (G)	3778.0Aab	3318.6Ba	2972.6Cb	1470.0Dab
Conventional + G	3781.0Aab	2754.3Bb	2926.0Bbc	1331.3Cb
Conventional	3524.6Ab	2854.0Bb	2674.3Bc	1406.3Cab
Mean	2810.2			
CV, %	4.71			

* Means followed by the same lowercase letter in the column and the same uppercase letter in the row, does not differ by Tukey's test at 5% probability.

expressed consistently higher canopy to air temperature differences than plants in the fully irrigated treatment, indicating that the non-irrigated plants were experiencing high levels of water stress. Three days after the irrigation event canopy temperatures lower than that of the air temperature were observed in the fully irrigated treatment, indicating that plants were experiencing little to no restrictions on transpiration and therefore water stress at that time. On the contrary, plants in the non-irrigated treatment continued to show a higher level of water stress (remaining ~4°C higher).

The importance of practicing irrigation in agriculture is evident from the observed decrease in canopy temperatures of plants in the irrigated treatment. Irrigating crops helps prevent restrictions to transpiration and thermoregulation. According to Zhang et al. (2015), the use of irrigation has two important effects on adaptive corn and soybean yields in the central United States, limited water and extreme heat.

Differences found in canopy temperatures suggest that the use of deep tillage can be used as a management tool in minimizing the water stress in areas with soil compaction. One day before the irrigation event plants in treatments with deep tillage had lower canopy temperature and less variation between canopy and air temperature. According to Strudley et al. (2008), deep tillage increases water infiltration, internal drainage and aeration in the soil, and in turn increases rooting depth, intensity, and development. According to Jabro et al. (2015), deep tillage often provides healthier soil physical conditions that promote a more favorable soil environment for plant growth relative to no tillage system.

Yield

2013 Season results

Interaction was observed between the soil and the irrigation treatments in relation to seed yield (Table 3). Deep tillage and deep tillage + gypsum treatments produced higher grain yield than that of the conventional and conventional +gypsum treatments. Within fully irrigated, +1 deficit, +2 deficit and non-irrigated irrigation treatments, deep tillage treatment produced 22, 33, 31, and 28% more grain than the conventional treatment, respectively. Similarly the deep tillage + gypsum treatments yield was 14, 33, 40, and 48% greater than the conventional + gypsum treatment in the fully irrigated, +1 deficit, +2 deficit, and non-irrigated treatments, respectively (Table 3). No effect on yield was observed as a result of the gypsum amendment. No differences in yields were found in any of the irrigation treatments between deep tillage and deep tillage + gypsum treatments or between conventional and conventional + gypsum treatments (Table 3).

Within all soil treatments, the non-irrigated treatments had significantly lower yields than all other irrigation treatments, and no clear differences in yields were detected between the +1 deficit and +2 deficit treatments (Table 3). Within the deep tillage or deep tillage + gypsum treatments, there was no significant difference found between yields in the fully irrigated and +1 deficit. However, within the conventional and conventional + gypsum soil treatments, the fully irrigated treatments yielded higher than all others irrigation treatment. Across the conventional soil treatment the fully irrigated treatment produced 18, 23, and 71% higher yield than +1 deficit, +2 deficit and non-irrigated plots, respectively. Similarly within the conventional + gypsum fully irrigated treatment produced 27, 37, and 79% more grain than +1 deficit, +2 deficit, and non-irrigated plots, respectively (Table 3).

2014 Season Results

No significant yield interaction was detected between the soil and irrigation treatments (Table 4). The deep tillage treatment resulted in a 9% yield increase to that of the conventional treatment yield (Table 4). Non-irrigated plots had significantly lower seed yields than all other irrigation treatments. No differences in seed yield was detected between fully irrigated and +1 deficit treatments. On average the +2 deficit treatment plots produced 6 and 5% less grain than the fully irrigated and +1 deficit treatments, respectively. The non-irrigated treatments produced, on average, significantly less seed yield than all other irrigation treatments. Non-irrigated treatment plots on average

Table 4. Seed yield to the irrigation and soil treatment. 2014 season; Stuttgart, AR, 2015.

Soil treatment	Seeds yield
	kg ha^{-1}
Deep tillage	4807.3a*
Deep tillage + gypsum (G)	4554.4b
Conventional + G	4504.5b
Conventional	4352.1b
Irrigation treatment	
Fully irrigated	4884.6a
+1 deficit	4837.9a
+2 Deficit	4594.5b
Non-irrigated	3901.3c
Mean	4554.0
CV, %	7.1

* Means not followed by the same letter in the column differ by Tukey's test at 5% probability.

produced 20, 19, and 15% less grain than fully irrigated, +1 deficit, and +2 deficits, respectively (Table 4). A greater amount of rainfall was experienced this growing season relative to 2013 and 2015 seasons (Fig. 3). It is likely that the relatively high amount of rainfall minimized the irrigation treatment effects.

2015 Season Results

Interaction was detected between the soil and the irrigation treatments in relation to seed yield (Table 3). Again deep tillage and deep tillage + gypsum treatments produced higher grain yields. Within all irrigation treatments, the deep tillage treatment produced 10, 15, 18, and 15% more yield than conventional in the fully irrigated, +1 deficit, +2 deficit and non-irrigated, respectively (Table 3). The only clear difference in yield between the deep tillage + gypsum treatment and the conventional + gypsum was that within the +1 deficit plots, deep tillage + gypsum treatment yielded 17% more grain than the conventional + gypsum (Table 3). There were no differences for the other irrigation treatments and the gypsum in each irrigation treatment. Again no effect on yield was observed as a result of the gypsum amendment. Within all irrigation treatments, no clear differences in yields was found between deep tillage and deep tillage + gypsum treatments or between conventional and conventional + gypsum treatments (Table 3).

Within all soil treatments the fully irrigated treatment resulted in higher yields than all other irrigation treatments, and the non-irrigated treatment resulted in lower seed yields than all other irrigation treatments. With exception of the deep tillage + gypsum soil treatment, no difference in yields detected between the +1 deficit and +2 deficit treatments (Table 3).

Yield Discussion

Deep tillage provides healthier soil physical conditions (Jabro et al., 2015), which makes soils more favorable for plant growth. In this study an overall soil penetration resistance reduction was observed in the soils treated with deep tillage relative to the conventionally treated soils. According to Jabro et al. (2015), deep tillage practices induce greater soil loosening, disturbance, and manipulation intern lowering soil penetration resistance and creating more soil macropores. The penetration resistance reduction in the deep tillage treatment was extremely evident at a depth of 7 to 15 cm indicating that deep tillage also caused a disruption in the compaction layer observed in the conventionally treated soil (Fig. 2). The higher yields observed in the deep tillage treatment are associated with, the overall reduction in penetration resistance as well as the disruption of the compaction layer at 7 to 15 cm in the soil subsurface. In addition it has been noted that deep tillage practices cause a reduction in soil compaction, which increases water infiltration, internal drainage, and aeration in the soil (Strudley et al., 2008; Jabro et al., 2015), which are all important for obtaining higher soybean yield. Therefore one may speculate that the deep tillage-treated soils in this study had higher infiltration, internal drainage, and aeration, which contributed to greater plant yields and overall plant growth. Furthermore the compaction layer present in the soil subsurface of the conventional treatment was a limiting factor to soybean yield in this study. Beulter and Centurion (2004) noted that compaction layers caused decrease in the root density, root dry matter, and reduction in soybean yield. Overall seed yield increased as the allowable deficit got smaller in the irrigation treatments. The irrigation effects on soybean yield are likely a result of increases in stomatal conductance, shoot dry mass, root dry mass, as well as reduction in canopy temperature, observed in the lower deficit irrigation treatments. Furthermore nodules per plant and nodules dry mass increased as deficit was decreased and was the highest in the fully irrigated treatment. According to Brandelero et al. (2009), nodulation is a determining factor in seed yield and is correlated 40% with grain production. Therefore the higher number of nodules per plant and nodule dry mass observed for plants in the wetter irrigation treatments (highest in the fully irrigated treatment) is likely the greatest contributor to the increase in soybean yields observed among the irrigation treatments.

Inversely, the lower seed yield in the higher deficit irrigation treatments were likely associated with a decrease in photosynthesis due to water stress, evident from the higher canopy temperatures and lower stomatal conductance observed in the non-irrigated treatment. According to Ribas-Carbo et al. (2005), water stress, induced by controlled watering, caused a progressive and concomitant decrease in net photosynthesis. Doss et al. (1974) examined effects on seed yield in response to water stress at several stages of soybean growth, and found that yield reductions in treatments that experienced water stress, at any portion of the season treatments that experiences water stress all season.

SUMMARY

Increases in yields associated with deep tillage practices were observed across all 3 yr of this study. Production systems that suffer from yield loss as a result of a compaction layer present in the soil subsurface may consider deep tillage practices. This study has shown that deep tillage can be a beneficial management tool to combat the negative consequences of compaction layers in soybean production. In addition, this study suggests that using deep tillage can allow for more effective water use and may lead to reduction in water use in soybean production systems. The use of gypsum amendment or associate combined deep tillage gypsum did not show effects on grain production in the soil type examined in this study. More studies on various soil types are needed to determine applicability and any potential effects on soybean yields.

The use of irrigation is a recommended practice for maximizing soybean yields. Irrigation practices combat the negative consequences of water stress experiences by the plants throughout the course of the growing season. In this study reducing the allowable water deficit induced greater crop growth, nodulation, and resulted in higher-yielding soybean. As the irrigation deficit was increased the soybean seed yield decreased. However, within deep tillage treatments no difference in yield was observed between the +1 deficit and the fully irrigated irrigation treatments. Furthermore the +1 deficit was associated with a reduction in water use, suggesting that when deep tillage practices are being used in soybean production systems with compaction layers, greater allowable deficits can be employed in scheduling soybean irrigation, likely due to improved water holding capacity of the soil. As a result, applying deep tillage practices in soybean production systems with similar soil conditions can lead to a reduction in water use and associated cost with that water use by using an increased deficit. Thus for Arkansas conditions, we recommend using the +1 deficit threshold for deep tillage. For conventional tillage the current AIS recommendations appear appropriate. We have concluded there is no benefit to gypsum amendment in this soil type; thus no change in AIS recommendations are warranted for this practice.

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