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AGRONOMY AND SOILS

Influence of Irrigation Pattern on Effectiveness of Furrow Irrigation of Cotton

Earl D. Vories* and Andrea S. Jones

ABSTRACT

Cotton is one of the major crops in the Mid-South growing region of the U.S. and producers there often farm numerous fields spread across a large area. Although sufficient groundwater is available for surface irrigation in many areas, the supply and cost of labor is always a concern. Producers commonly employ patterns such as every-other-furrow irrigation to allow them to irrigate fields in one set and thereby avoid the time and labor required to change sets. In many years there is sufficient rainfall that no obvious deleterious effect is observed from the non-irrigated furrows, however producers are concerned that yield could be reduced. A study was conducted at the University of Missouri Fisher Delta Research Center near Portageville during the 2014 through 2016 growing seasons to investigate the impact of different furrow irrigation patterns on cotton yield and canopy properties. Although yield loss due to waterlogging is a constant concern in the region, in 2014, with four irrigations followed by ≥ 25 mm of rain within the subsequent three days, all irrigated plots yielded significantly more seed cotton than the rainfed treatment. Canopy temperature, plant height, and normalized difference vegetation index were all effective in differentiating between the rainfed and irrigated treatments including differences among some of the irrigation pattern treatments.

Cotton (*Gossypium hirsutum* L.) is one of the major crops in the U.S. Mid-South. The region has a sub-humid climate and irrigation has been a more recent addition to the production systems in those states than for farmers in the more arid western U.S. In the Mid-South, cotton usually can be produced without irrigation and water stress comes from excess as well as deficient water. Although furrow irrigation in many large Mid-South fields can take 12 hours or longer, rainfall shortly after irrigation can increase substantially the waterlogging period. Hearn and Constable (1984) stated, "Irrigation decisions are compromises between reducing the risk of water stress and increasing the risk of waterlogging."

Many researchers have studied the effect of differing levels of water stress on cotton; however, much of the work was done in arid regions where irrigation is essential for production. Garrot et al. (1988) reported increased yield with an increase in the number of irrigations and Fangmeier et al. (1989) observed that seed cotton yields increased with the amount of water applied. Grimes et al. (1969) showed lint yield initially increased with the amount of water applied, but then decreased at higher levels of applied water. A similar response was observed by DeTar (2008). Averaged over the years 2002, 2003, 2004, and 2006, cotton yield increased steadily following drip irrigation applications from 314 mm through 654 mm. Irrigation levels above 654 mm had little effect on yield. In Turkey, Onder et al. (2009) observed increasing yields with increasing water application; however, in the U.S. Mid-South, Vories et al. (2015) reported decreasing yield following higher total irrigation volume, and their recommended irrigation treatment produced significantly less yield than treatments where less total irrigation water was applied. In more humid areas such as the U.S. Mid-South, untimely rains negatively impact yields for irrigated cotton as well as other crops.

In recent years, Mid-South cotton producers have turned to precision agriculture to improve yield and yield stability. McKinion et al. (2001) used modeling and information from a Mississippi farm to predict that an increase of 322 kg lint ha^{-1} could be obtained by using an average increase of 2.6 cm water and an average decrease of 35 kg nitrogen ha^{-1}. Yield monitors are an important component of precision agriculture. Larson et al. (2005) reported that the rate of yield monitor adoption by cotton farmers lagged behind the rates of adoption for grain yield monitors. The accuracy and reliability of cotton yield monitors has improved and they are now standard on new pickers. Although cotton yield monitors do not perform adequately with a single calibration for multiple vari-

E.D. Vories*, Cropping Systems and Water Quality Research Unit, USDA–ARS, Fisher Delta Research Center, PO Box 160, Portageville, MO 63873 and A.S. Jones, PhytoGen Cottonseed, 759 South Walnut Street, Steele, MO 63877.
*Corresponding author: Earl.Vories@ars.usda.gov

eties (Vories et al., 2018), satisfactory correlation with observed weights can be obtained for a single variety.

Sensors can collect relatively dense geo-referenced datasets of spatially variable properties while traversing a field. These site-specific sensors offer more timely results and the ability to obtain higher spatial resolution than do traditional measurement methods that involve sample collection and laboratory analyses. Apparent electrical conductivity (EC_a) of the soil profile is a sensor-based measurement that can provide an indirect indicator of important soil physical and chemical properties. For saline soils, most of the variation in EC_a can be related to salt concentration (Williams and Baker, 1982); however, most Mid-South soils are low in salinity and in nonsaline soils, conductivity variations are primarily a function of soil texture, moisture content, and cation exchange capacity (Rhoades et al., 1976). In general, increasing EC_a values within a field correspond to finer textured soils. Freeland et al. (2008) noted areas of high sand content in the region, commonly called sand blows and fissures, which can be important to irrigation management due to the low plant-available water associated with sand. Although the sand blow areas should appear as relatively low EC_a, many soils used for cotton production have high sand content and the sand blows can be difficult to differentiate from the surrounding soil.

The problem of soil variability in research has been addressed traditionally by reducing plot size and assuming the resulting experimental units to be homogeneous with no spatial autocorrelation, at least within replicates. Larger-plot data are often analyzed with the same assumptions; however, inferences developed from traditional analysis of variance (ANOVA) results are compromised when spatial autocorrelation is present in the data (Griffin et al., 2004), and site-specific yield data tend to be strongly positively spatially autocorrelated (Griffin et al., 2007). Furthermore, raw yield monitor data contain a variety of inherent errors. Sudduth and Drummond (2007) reported that 10 to 50% of observations in a given field should be removed. They developed software to identify the faulty data points (Sudduth and Drummond, 2007) and then refined it to simplify the process (Sudduth et al., 2012).

Geographic Information Systems (GIS) have been developed for managing and manipulating extensive datasets such as those created with precision agriculture (e.g., ArcMap; ESRI, Redlands, CA). Furthermore, because the high-density datasets tend to violate some of the assumptions inherent in traditional statistical methods, different types of analyses are required. As the concepts associated with spatial statistics have become better understood, software packages (e.g., GeoDa, Center for Spatial Data Science, Univ. of Chicago, Chicago, IL) have been developed for analyzing the large, spatially referenced datasets.

Finally, cotton producers in the Mid-South often farm numerous fields spread across a large area. Although sufficient groundwater is available for surface irrigation in many areas, the supply and cost of labor is always a concern. For surface-irrigated fields, producers commonly employ patterns such as every-other-furrow irrigation to allow them to irrigate fields in one set, negating the need for someone to return to the field to change sets and then again to stop irrigation. Although in many years there is sufficient rainfall that no obvious deleterious drought-stress effect on yield is observed, producers are always concerned that they are reducing yields using that strategy in dry years. Similarly, waterlogging from surface irrigation followed closely by rainfall is always a concern. The objective of this research was to investigate the impact of no irrigation and different furrow irrigation patterns on cotton yield and canopy characteristics.

METHODS AND MATERIALS

A field experiment was conducted in 2014 through 2016 on a Tiptonville silt loam soil (fine-loamy, mixed, thermic Typic Argiudolls) (USDA–SCS, 1971) located at the University of Missouri Fisher Delta Research Center Lee Farm near Portageville (36.40° N, 89.61° W). Although the whole experimental field was mapped with one mapping unit, soils in the region often contain more variability than is reflected in the original soil surveys. Furthermore, precision land grading and other operations also have impacted many soils in the region. To better determine the current variability of the soil, an EC_a survey was conducted on 18 November 2016 using a DUALEM-1HS sensor (Dualem Inc., Milton, ON, Canada) on approximately 18-m transects.

The test location had been in continuous cotton production for more than 50 yrs prior to establishing this experiment. Daily and hourly weather data were collected approximately 900 m from the study site and placed on the University of Missouri Agricultural Electronic Bulletin Board (AgEBB; http://agebb.missouri.edu/weather/realtime/hayward.asp). Nitrogen (134 kg N ha^{-1}) and potassium (34 kg K_2O ha^{-1}) were broadcast applied soon after planting each year. A composite soil sample collected from the study area each year indicated that no additional fertilizer was required. Standard pest management recommendations for producing irrigated cotton in Missouri were followed (Bradley et al., 2015). Herbicides, growth regulator, insecticide, and harvest aids were applied as blanket treatments to all plots. Following harvest each year, disc hippers were used to re-form the beds. Just before planting, a PrepMaster bed conditioner (Bigham Brothers, Inc., Lubbock, TX) was used to prepare the beds. Post-plant tillage was limited to one pass early in the season with an irrigation plow to remove any material from the furrows. All furrows were plowed, including the rainfed treatment.

The trial was arranged in a randomized complete block with a rainfed treatment (RF) and four furrow irrigation patterns: every furrow irrigated (EV); every other furrow irrigated employing the same furrows each time (EO); every other furrow irrigated, but alternating with each irrigation such that the furrows not irrigated in the previous application were irrigated in the subsequent application (ALT); and every third furrow (E3) irrigated. The treatments were replicated three times. The study was conducted in the same field each year and the same randomization of treatments was used. A leaking irrigation riser impacted the southernmost plot. Although the leak worsened over time, some effect could be seen in 2014; therefore, data from the plot were not included in the analyses for any year.

Table 1 summarizes the planting, irrigation, and harvest dates for the study. All plots were seeded at a rate of 13 seed m^{-1} with the cultivar PHY 339 WRF (Dow AgroSciences, Indianapolis, IN). All plots were 16 rows wide with 0.97-m row spacing and 70-m long, with an 8-row rainfed buffer maintained between irrigation treatments to minimize the impact of lateral water movement. Irrigated plots received furrow irrigation every week with < 25 mm of rainfall observed; however, the period before irrigation began was extended during June 2016 when plants were small to minimize waterlogging. Irrigation was terminated mid-August each year based on University of Missouri recommendations. To investigate the effectiveness of the different treatments, tensiometers (Irrometer Company, Riverside, CA) were installed in row 5 of each plot at 15-cm and 30-cm depths in early June and readings were taken approximately each weekday.

Table 1. Planting, irrigation, and harvest dates in 2014 through 2016

Event	Date
2014	
Planting	8 May
Irrigation	25 June; 11, 23, 30 July; 6, 12 August
Harvest	2 October
2015	
Planting	27 May
Irrigation	6, 23, 28 July; 6, 18 August
Harvest	4 November
2016	
Planting	31 May
Irrigation	7, 22 July
Harvest	4 November

A set of tractor-mounted sensors (Table 2) was driven through each plot on 6 August 2014, 4 August 2015, and 6 August 2016 to measure canopy height, temperature, and reflectance. The sensors were newly purchased so no additional calibration was done. Normalized difference vegetation index (NDVI) data, calculated from the reflectance measurements, was included in the sensor output. The sensors were located approximately 76 cm directly above the crop rows of each plot and aimed vertically, except for the canopy temperature sensors, which were aimed forward at a 45° angle to increase the number of plants within the field of view and minimize any impact of soil. Readings were made between 1200 h and 1700 h CDT. The sampling locations were recorded using Differential Global Positioning System readings associated with each sensor reading to provide positional information with an accuracy of 1 m or better. In 2014, readings were made from rows 5 and 12, except for the every third furrow treatment, where rows 3 and 12, with a non-irrigated furrow on either side, were selected to represent the driest portion of the plot. To increase the portion of the plot measured by sensors in 2015 and 2016, readings were made from rows 3, 6, 11, and 14, except for the every third furrow treatment, where rows 2, 5, 11, and 14, with a non-irrigated furrow on either side, were used.

Table 2. Mobile sensors used in study

Property	Manufacturer	Model
Sensor location	Raven Industries (Sioux Falls, SD)	RPR 210
Canopy height	Senix Corporation (Hinesburg, VT)	TSPC-30S1-SK232
Canopy temperature	Everest Interscience (Tucson, AZ)	4000L
Canopy reflectance	Holland Scientific (Lincoln, NE)	Crop Circle ACS-430

Cotton was harvested with a Case IH 2155 (Case IH, Racine, WI) picker equipped with an Ag Leader Insight (Ag Leader Technology, Ames, IA) yield monitor system. The yield monitor was calibrated by placing the cotton from each plot in a boll buggy equipped with scales. Yield data were processed with the Yield Editor program (v. 2.07; Sudduth et al., 2012) using the Automated Yield Cleaning Expert (AYCE) function and recommended settings. Any extraneous data points that appeared to be outside of the field and were not removed by the AYCE were manually removed from the data set. The spatially dense yield and sensor data were analyzed using the spatial error model in GeoDa 1.8.16. Tensiometer readings were compared with aspatial ANOVA using SAS 9.4 for Windows (SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

Figure 1 shows the findings from the EC_a survey conducted in the study field for a depth of exploration of 1.6 m (DUALEM Inc., 2014). A total of 21 transects were made, resulting in 722 values recorded within the field. The values ranged from 9.2 to 25.1 mS m^{-1}, with 60% of the values between 11.5 and 14.5. Although the data have not been calibrated to soil texture, there do not appear to be any areas of especially high sand or clay content that would excessively influence an irrigation study.

Weather. Figure 2 includes the cumulative growing degree days (GDD) using 15.6° C as the base temperature, and rainfall from planting through early November for each year, along with the dates of planting, furrow irrigation, and harvest. Despite receiving more than 200 mm of rainfall in April 2014, no rainfall was received during the first week of May and the study was planted on 8 May, a typical cotton planting date for the region. A total of 1254 GDD were accumulated between planting and harvest and even though 461 mm of rainfall was received from planting through harvest, six irrigation applications were applied based on the study protocol (Fig. 2a; Table 1). Four of the irrigations (25 June, 11 and 23 July, and 6 August) were followed by rainfall of ≥ 25 mm within the next 3 d.

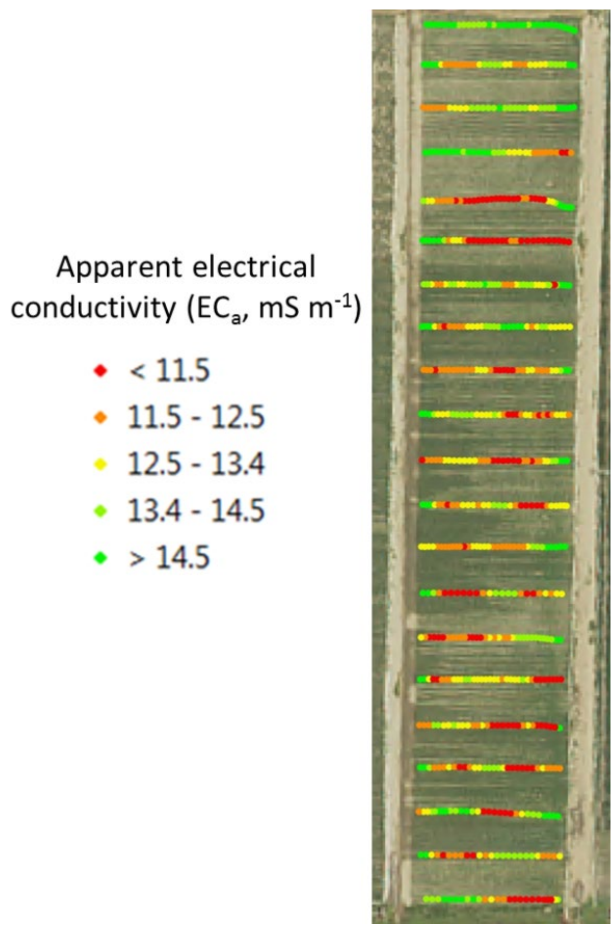

Figure 1. Apparent electrical conductivity (EC_a) values in study field.

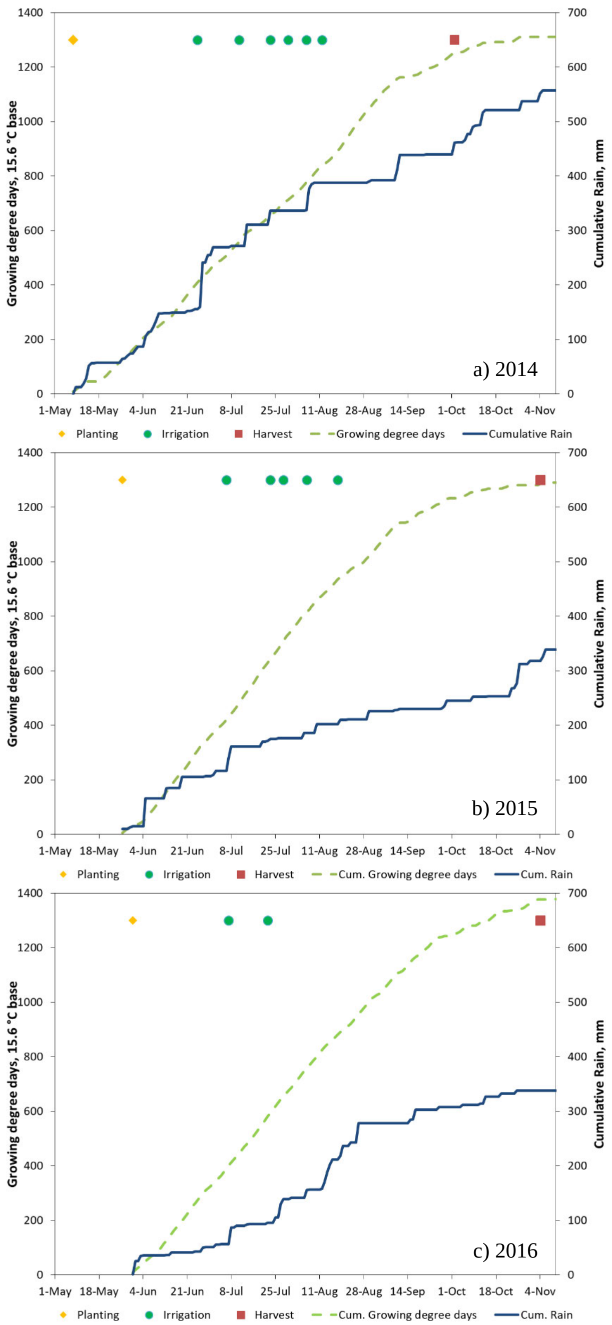

Figure 2. Dates of planting and irrigation along with cumulative growing degree days and rainfall from planting through early November for a) 2014, b) 2015, and c) 2016.

Although less rainfall was received in April 2015 than the previous year (136 mm vs. 212 mm) and no rainfall was received from 1 through 6 May, 98 mm were received during the following 2 wks. Planting was delayed until 27 May, which is later than desired but still within the acceptable range for the region. Even with the later planting date, similar numbers of GDD were received in 2015 (1285 vs. 1254 GDD) (Fig. 2b). Considerably less rainfall was received from planting through harvest than during the previous year (318 mm vs. 461 mm). Five irrigations were applied (Table 1), with one (6 July) followed by 44 mm of rainfall over the next 2 d.

With < 25 mm of rainfall recorded during the first 26 d of April and daily maximum temperatures as high as 27°C, the study was planted 26 April 2016. However, 57 mm of rainfall was recorded during the following 4 d and more than 100 mm during the first 3 wks after planting. Waterlogged conditions resulted in a non-uniform stand; therefore, the remaining plants were destroyed and the field was replanted on 31 May 2016. As in 2015, the planting date was later than desired but still within the acceptable range for the region. Even with the late planting date, similar numbers of GDD were received in 2016 (1376 vs. 1254 and 1285 GDD for 2014 and 2015, respectively) (Fig. 2c). A total of 338 mm of rainfall was received from planting through harvest, between the amounts for the previous years (461 and 318 mm for 2014 and 2015, respectively). The timing of the rainfall resulted in only two irrigation applications (Table 1), with one (7 July) followed by 30 mm of rainfall the following day.

Soil Moisture. Tensiometer readings were collected from early June through early August each year. For the 15-cm readings in 2014, significant differences among the five treatments were observed only on 31 July. Numerically, the least tension (wettest) was present in the RF treatment, which was not significantly different from the EV treatment. For the 30-cm readings in 2014, significant differences were observed on five dates (Fig. 3a). Surprisingly, values from RF cotton were never the greatest (driest). On 7 July, values from RF cotton were significantly greater than those from cotton in the EV treatment and not different from the other treatments. On 29 and 30 July, values were significantly less than those from cotton in the ALT treatment and not different from the other treatments. On the final two monitoring dates, values from RF cotton were not significantly different from any other treatment. Perhaps more surprising than the values at any date, all treatments tended to get drier at 30 cm even with irrigation. All treatments were wetter on 2 July than on 27 June; however, that was probably due to the 114 mm of rain in the week following the 25 June irrigation more than the irrigation itself. Getting water to move very deeply into the soil in the Mid-South following irrigation is a common problem and the short row lengths in this study likely exacerbated the situation.

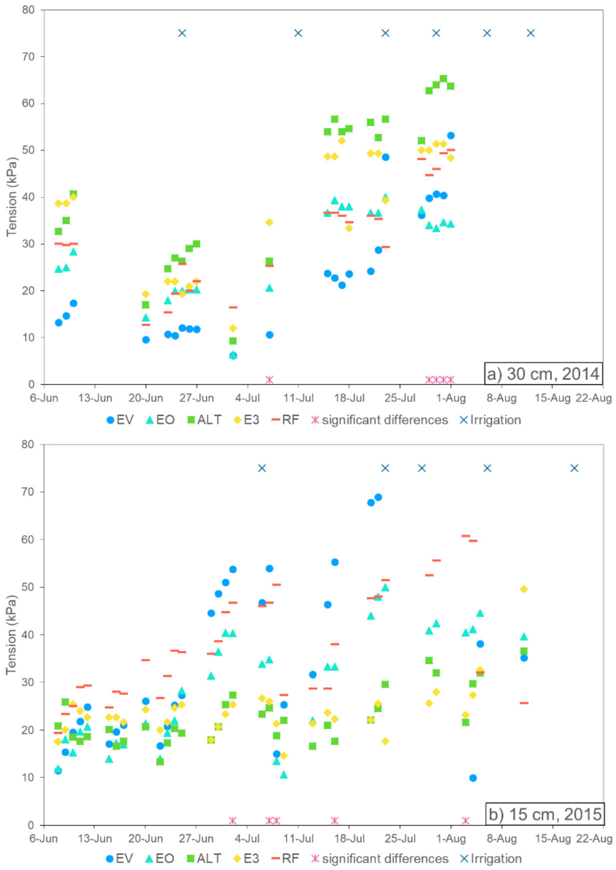

Figure 3. Soil moisture tension a) at 30 cm in 2014 and b) at 15 cm in 2015.

In 2015, no significant differences were observed among the five treatments for the 30-cm readings, but significant differences were observed on five dates for the 15-cm readings (Fig. 3b). Values for cotton in the EV treatment were drier than expected and on four dates the sensors lost contact with the soil during the season and showed a reading of zero. Tensiometers at a depth as shallow as 15 cm can be disturbed fairly easily, causing them to lose soil contact; however, this should not affect one treatment more than the others.

No significant differences among the treatments were observed in the tensiometer readings in 2016. The observations in this study demonstrate a common problem with soil moisture sensors in general and especially tensiometers. Installing, reading, and in some cases maintaining, the sensors requires a lot of work. When the readings are variable, many producers believe that the information is not worth the effort.

Yield. Table 3 presents the results of the seed cotton yield analysis based on the yield monitor data analyzed with the GeoDa spatial statistics program. As expected, spatial autocorrelation was present for all of the data; therefore, the spatial error model was used as recommended by Griffin et al. (2007). The whole plot values represent the yield from all 16 rows. In 2014, even with 461 mm of rain between planting and harvest, the RF cotton yielded significantly less seed cotton than the other treatments. Little difference in yield was observed among the irrigated treatments, although cotton in the EV treatment yielded significantly more than either cotton from the EO or ALT treatment. Surprisingly, with little lateral water movement observed, cotton yield in the E3 treatment was not significantly different from any other irrigated treatment. Even with four irrigations followed closely by rainfall and the frequent (weekly) irrigation schedule, cotton in the EV treatment was not impacted by waterlogging. Although many farmers follow the weekly schedule for convenience in scheduling labor, the practice does not adequately take into account the moisture status of the soil or crop. In addition, although concerns about the effectiveness of every-other-furrow irrigation during dry years led to this study, even in this relatively wet year, EV cotton yielded significantly more seed cotton than EO or ALT cotton, although the differences were < 100 kg seed cotton ha^{-1}.

Table 3. Seed cotton yield from 2014 through 2016

Irrigation treatment	Seed cotton yield, kg ha^{-1}	
	Whole plot	Sensed rows only
2014		
Every furrow	3237 a[z]	3543 a
Every other furrow	3164 b	3545 a
Every other furrow, alternating	3144 b	3593 a
Every third furrow	3195 ab	3144 b
Rainfed	3070 c	3491 a
2015		
Every furrow	4182 ab	4007 a
Every other furrow	4118 b	3936 a
Every other furrow, alternating	4198 a	4023 a
Every third furrow	4127 ab	3974 a
Rainfed	3891 c	3713 b
2016		
Every furrow	3048 c	3181 ab
Every other furrow	3099 bc	3014 c
Every other furrow, alternating	3161 ab	3093 abc
Every third furrow	3205 a	3212 a
Rainfed	3182 ab	3032 bc

[z] Means within a year and column followed by the same letter are not significantly different ($p < 0.05$).

In 2015, even with the later planting date, cotton yields for all treatments were greater than the previous year and, like the previous year, RF yielded significantly less seed cotton than the other treatments (Table 3). ALT cotton yielded significantly more than EO cotton, but the difference was only 80 kg seed cotton ha^{-1}. Yield for E3 cotton was not significantly different from other any irrigated treatment. With only one irrigation followed closely by rainfall, waterlogging did not impact these data and the tensiometer readings support that conclusion.

Even though the planting date in 2016 was only 4 d later than 2015 (Table 1), yields for all treatments were lower (Table 3). Although there were only two irrigations and only one was followed closely by rain, the EV cotton yielded significantly less seed cotton than all other treatments except EO cotton. Yield of RF cotton was not significantly different from any irrigated treatment except EV cotton, and somewhat surprisingly, E3 cotton yielded significantly more seed cotton than either EV or EO cotton. With only two irrigations and only one of them followed closely by rainfall, it seems unlikely that the lower yield following EV irrigation resulted from waterlogging and the tensiometer data did not indicate waterlogging. It is important to note that the range from highest to lowest yielding treatments was only 157 kg seed cotton ha^{-1} (Table 3). Vories et al. (2014) observed rainfed cotton yielded equal to irrigated cotton in 2010, but not in 2011 or 2012 in their study at a nearby field at the same location. Similarly, Vories et al. (2007) observed a lack of yield response to irrigation in 2003, but not in 2001 or 2002 in another Mid-South location.

Canopy Sensors. An important assumption in many precision agriculture procedures, particularly real-time site-specific applications, is that sensor data from a limited number of rows can be interpolated and extrapolated over much larger areas. If the assumption is true, then yields from the sensed rows should be similar to that from the larger areas. Therefore, in addition to the yield from all 16 plot rows, seed cotton yield was also compared from only the rows where sensor data were collected (Table 3). In 2014, when only two of the 16 rows were monitored, there were differences observed from the whole plot data, with E3 cotton producing the lowest yield compared to RF cotton.

Findings from the 2014 sensor readings are included in Table 4. The ultrasonic sensors measure the distance from the sensor to a target; therefore, the canopy height is determined by measuring the height of the sensor above the ground and subtracting the sensor reading. The heights of the sensors and plant heights were measured multiple times as a check on the sensors, but not in every plot. In this case, the differences among treatments were of interest and not the absolute height; therefore, small errors in calibration were not considered important.

Table 4. Canopy sensor results from 2014 and 2016

Irrigation treatment	Canopy property		
	Temperature,°C	Height, cm	NDVI
2014			
Every furrow	30.5 c[z]	129 a	0.850 a
Every other furrow	32.3 b	126 b	0.836 b
Every other furrow, alternating	33.2 ab	127 b	0.840 b
Every third furrow	28.4 d	126 b	0.828 c
Rainfed	34.2 a	125 c	0.832 c
2016			
Every furrow	30.4 c	82 a	0.832 a
Every other furrow	30.6 c	75 b	0.786 b
Every other furrow, alternating	30.6 c	74 bc	0.775 bc
Every third furrow	31.2 b	72 c	0.772 c
Rainfed	31.7 a	67 d	0.723 d

[z] Means within a year and column followed by the same letter are not significantly different ($p < 0.05$).

The canopy temperature sensors were compared to each other and to a handheld sensor measuring known conditions (e.g., ice water) to ensure consistent readings among the sensors. Canopy temperature is known to be affected by water stress and RF cotton had the highest temperature (34.2°C), though not significantly hotter than ALT cotton. E3 cotton, which had a dry furrow on either side of the sensed rows and therefore would be expected to show drought stress, had the lowest temperature (28.4°C), and EV cotton had a lower temperature than either EO or ALT cotton. Not surprisingly, EV cotton produced the tallest plants (129 cm) and the highest NDVI (0.850), which is correlated to crop biomass. RF cotton had the shortest plants (125 cm) and the lowest NDVI of all treatments except E3 cotton. Canopy temperature differences were not observed between irrigated and rainfed plots in late July or early August in previous research, whereas differences in height and NDVI were observed in two of three years (Vories et al., 2014).

To have yields of the sensed rows closer to those of the whole plots, the number of rows measured with canopy sensors was increased to four per plot in 2015. Although yields from the four sensed rows were nearer to the yields from the whole plots than in 2014, the statistical comparisons were different, with no significant differences among the four irrigated treatments (Table 3). However, the GPS system for the canopy sensors failed when the data were collected and it was not possible to repeat the measurements so no canopy sensor data were included from 2015.

Four rows were sensed in 2016 and the yield levels for those rows were similar to the whole plot values (Table 3). The largest difference among the comparisons was yield for EV, which was lowest for the whole plot but was not significantly less than any other treatment for the sensed rows. RF had the highest temperature, the shortest plants, and the lowest NDVI, whereas EV had the tallest plants and the highest NDVI (Table 4). Plants were shorter and had lower NDVI values in 2016 than 2014, probably due to the later planting date.

SUMMARY AND CONCLUSIONS

The study included rainfed cotton and four furrow irrigation patterns. The study was planted in May of each year, although two of the three years it was in the final week of May. Furrow irrigations were scheduled when < 25 mm of rainfall was observed during a week. Although the scheduling method does not adequately account for soil moisture and is therefore generally discouraged in favor of water balance or soil moisture sensing methods, it is widely used by producers to simplify scheduling their labor forces. Tensiometers were used to track soil moisture but not for scheduling irrigations.

The primary conclusions from the study were (1) although fear of yield loss due to waterlogging is a frequent reason cited for delaying irrigation in sub-humid areas such as the Mid-South, the data cast doubt on waterlogging as the cause of the observed difference: in 2014, with four irrigations followed by ≥ 25 mm of rain within the subsequent three days, all irrigated plots yielded significantly more seed cotton than RF. In 2016, when RF outyielded an irrigated treatment, there were only two irrigations and only one followed closely by rain. (2) When two of 16 rows were measured with canopy sensors (2014), cotton yields in the sensed rows and the whole plot differed, suggesting that the findings from sensors might not be representative of the larger area. When four of 16 rows were measured in 2015 and 2016, the yields from the four sensed rows and from all 16 rows more closely agreed. (3) Canopy temperature, plant height, and NDVI were all effective at differentiating between rainfed and irrigated cotton including differences among some of the irrigated treatments. However, additional research will be required to apply the findings to uses such as variable rate irrigation prescriptions and that research is currently being conducted. (4) Although questions about the impact of irrigating less than every furrow during an especially dry year led to the study, no extremely dry growing season occurred during the study. The driest was 2015, which had 318 mm of rainfall between planting and harvest. Additional studies conducted in conjunction with producers would also address issues of scale on the longer furrows that were not considered in this study.

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DISCLAIMER

Mention of trade names or commercial products is solely for purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

REFERENCES

Bradley, K.W., L.E. Sweets, W.C. Bailey, M.M. Jones, and J.W. Heiser. 2015. Missouri pest management guide: Corn, grain sorghum, soybean, winter wheat, rice, cotton. Univ. Mo. Ext. M171. Available at https://extensiondata.missouri.edu/pub/pdf/manuals/m00171.pdf (verified 2 Oct. 2018).

DeTar, W.R. 2008. Yield and growth characteristics for cotton under various irrigation regimes on sandy soil. Agr. Water Manage. 95:69–76.

DUALEM Inc. 2014. DUALEM-1HS User's Manual. Milton, ON, Canada.

Fangmeier, D.D., D.J. Garrott, Jr., S.H. Husman, and J. Perez. 1989. Cotton water stress under trickle irrigation. Trans. ASAE 32(6):1955–1959.

Freeland, R.S., J.T. Ammons, and C.L. Wirwa. 2008. Ground penetrating radar mapping of agricultural landforms within the New Madrid seismic zone of the Mississippi embayment. Appl. Eng. Agric. 24(1):115–122.

Garrott, D.J., Jr., D.D. Fangmeier, and S.H. Husman. 1988. Cotton management using infrared thermometry. ASAE Paper No. 88-2506, St. Joseph, MI.

Griffin, T.W., J.P., Brown, and J. Lowenberg-DeBoer. 2007. Yield monitor data analysis protocol: a primer in the management and analysis of precision agriculture data. Site Specific Management Center Publication. SSMC, West Lafayette, IN. Available at http://www.agriculture.purdue.edu/SSMC/ (verified 2 Oct. 2018).

Griffin, T.W., D.M. Lambert, and J. Lowenberg-DeBoer. 2004. Testing for appropriate on-farm trial designs and statistical methods for precision farming: A simulation approach. Proceedings of the 7th International Conference on Precision Agriculture and Other Precision Resources Management. 25-28 July 2004, Minneapolis, Minnesota. Precision Agriculture Center; Univ. Minnesota St. Paul, MN.

Grimes, D.W., H. Yamada, and W.L. Dickens. 1969. Functions for cotton (*Gossypium hirsutum* L.) production from irrigation and nitrogen fertilization variables. I. Yield and evapotranspiration. Agron. J. 61(5):769–773.

Hearn, A.B., and G.A. Constable. 1984. Irrigation for crops in a sub-humid environment VII. Evaluation of irrigation strategies for cotton. Irrig. Sci. 5(2):75–94.

Larson, J.A., R.K. Roberts, B.C. English, R.L. Cochran, and B.S. Wilson. 2005. A computer decision aid for the cotton yield monitor investment decision. Comp. Elec. Agric. 48:216–234.

McKinion, J.M., J.N. Jenkins, D. Akins, S.B. Turner, J.L. Willers, E. Jallas, and F.D. Whisler. 2001. Analysis of a precision agriculture approach to cotton production. Comp. Elec. Agric. 32:216–234.

Onder, D., Y. Akiscan, S. Onder, and M. Mert. 2009. Effect of different irrigation water level on cotton yield and yield components. African J. Biotech. 8(8):1536–1544.

Rhoades, J.D., P.A. Raats, and R.J. Prather. 1976. Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. Soil Sci. Soc. Am. J. 40:651–655.

Sudduth, K.A., and S.T. Drummond. 2007. Yield editor: Software for removing errors from crop yield maps. Agron. J. 99:1471–1482.

Sudduth, K.A., S.T. Drummond, and D.B. Myers. 2012. Yield Editor 2.0: Software for automated removal of yield map errors. ASABE Paper No. 121338243, St. Joseph, MI.

United States Department of Agriculture, Soil Conservation Service [USDA–SCS]. 1971. Soil survey of Pemiscot County, Missouri. USDA, Washington, DC.

Vories, E.D., R. Hogan, P. Tacker, R. Glover, and S. Lancaster. 2007. Estimating the impact of delaying irrigation for Midsouth cotton on clay soil. Trans. ASABE 50(3):929–937.

Vories, E., A. Jones, G. Stevens, and C. Meeks. 2018. Variety effects on cotton yield monitor calibration. *In* Proceedings of the 14th International Conference on Precision Agriculture (unpaginated). International Society of Precision Agriculture, Monticello, IL. Available at https://www.ispag.org/proceedings/?action=abstract&id=5138&search=authors (verified 2 Oct. 2018).

Vories, E.D., A.S. Jones, K.A. Sudduth, S.T. Drummond, and N.R. Benson. 2014. Sensing nitrogen requirements for irrigated and rainfed cotton. Appl. Engr. Agric. 30(5):707–716.

Vories, E.D., W.E. Stevens, K.A. Sudduth, S.T. Drummond, and N.R. Benson. 2015. Impact of soil variability on irrigated and rainfed cotton. J. Cotton Sci. 19(1):1–14.

Williams, B.G., and G.C. Baker. 1982. An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. Australian J. Soil Res. 20:107–118.