The *Journal of Cotton Science 19:1–14 (2015)*
http://journal.cotton.org, © The Cotton Foundation 2015

AGRONOMY AND SOILS

Impact of Soil Variability on Irrigated and Rainfed Cotton

Earl D. Vories*, William E. (Gene) Stevens, Kenneth A. Sudduth,
Scott T. Drummond, and N. Ray Benson

ABSTRACT

Cotton is a vital component of the economies of Mid-South states. Producers and landowners are looking for ways to reduce the variability of irrigated yields, and soil apparent electrical conductivity (EC_a) is a readily obtained parameter that can indicate soil variability. A study was conducted in 2011 and 2012 at the Fisher Delta Research Center in Portageville, MO, with the objective to determine the impact of soil spatial variability on yield and irrigation water use efficiency for cotton. Observed EC_a values were low, consistent with average sand contents that ranged from 59 to 82% in the upper 0.76 m of the soil profile. Spatial autocorrelation was present in the data and thus spatial analyses were used. In 2011, yields for two treatments were not significantly different from the mean field effect; however, the EC_a effect was significant, indicating that soil variability impacted yield more than irrigation differences for the two treatments. In 2012, yields for four of the six treatments were significantly different from the mean field effect; however, the EC_a effect was not significant. A quadratic equation was fit to the combined data from irrigated and rainfed plots in 2012. The resulting equation had a maximum of 3,372 kg ha^{-1} at 135 mm total irrigation and the median observed EC_a value (3.0 mS m^{-1}). Future efforts will include additional fields and environments, which should increase the understanding of the impact of soil variability and allow for improved selection of optimum management zones for site specific application of water and other inputs.

E.D. Vories*, Cropping Systems and Water Quality Research Unit, USDA–ARS, Fisher Delta Research Center, PO Box 160, Portageville, MO 63873; W.E. Stevens, Department of Plant Sciences, Fisher Delta Research Center, PO Box 160, Portageville, MO 63873; K.A. Sudduth and S.T. Drummond, Cropping Systems and Water Quality Research Unit, USDA–ARS, 269 Ag Engineering Bldg., Columbia, MO 65211; and N.R. Benson, University of Arkansas, Cooperative Extension Service, PO Box 717, Blytheville, AR 72316.
*Corresponding author: Earl.Vories@ars.usda.gov

Even with recent reductions in planting, cotton (*Gossypium hirsutum* L.) plays a vital role in the Mid-South economy. Rainfall in the Mid-South is sufficient most years to produce a cotton crop without irrigation and water stress often comes from excess as well as deficient water. Hearn and Constable (1984) stated, “Irrigation decisions are compromises between reducing the risk of water stress and increasing the risk of waterlogging.” However, timely irrigation has been shown to increase yields (Vories et al., 1991). Furthermore, many lenders have an irrigation requirement before making crop loans; therefore, the percentage of the crop that is irrigated has been steadily increasing.

Climate change is expected to increase the frequency and severity of drought in the region, further increasing the need for irrigation. Irrigation scheduling, the correct timing of irrigation during the growing season, is complicated in subhumid regions such as the Mid-South by factors such as cloud cover, rainfall, high relative humidity, and temperature swings caused by the movement of weather fronts. Most scheduling methods either measure or estimate soil water content. Many instruments have been developed to measure soil water content, but areas with highly variable soils such as the Mid-South generally require a large number of sensors to describe the soil moisture status of a field adequately. Wiring the sensors together in a network is seldom compatible with field operations. However, as sensor technology continues to improve and wireless networking of sensors becomes less costly and more reliable, direct measurement of soil moisture will become more common.

Most methods that estimate soil water status from weather data rely on a crop coefficient to relate crop evapotranspiration (ET_c) to short-grass reference evapotranspiration (ET_o) at different growth stages. The Arkansas Irrigation Scheduler (AIS) (Cahoon et al., 1990) uses a dual crop coefficient approach (Allen et al., 1998), where the effects of crop transpiration and soil evaporation are estimated separately to calculate a water balance to use in scheduling irrigation. The system balance represents the soil water deficit (SWD), or the difference between the soil's existing moisture content summed over the rooting depth and the moisture content of the soil at its well-drained upper limit approximately 24 h after surface water was removed. That limit is commonly field capacity (33 kPa tension) but can be higher on soils with limited internal drainage. Rooting depth is not used explicitly in the program, but is implicit in the choice of a maximum allowable SWD or management allowed depletion (MAD; i.e., the amount of water allowed to be used from the soil before applying irrigation). Cahoon et al. (1990) provided a detailed description of the program and Vories et al. (2009) provided information about changes to the program.

Though many researchers have studied the effect of differing levels of water stress on cotton, much of the work was done in arid regions where irrigation is essential for production. Garrot et al. (1988) reported the highest yields associated with the lowest levels of stress at irrigation, and Reginato (1983) observed a linear increase in lint production as the seasonal average stress index decreased. Hearn and Constable (1984) determined that water stress reduced yield up to 40 kg lint ha^{-1} d^{-1}. Cudrak and Reddell (1988) showed seed cotton yields decreased as the allowable water deficit increased. In the Mid-South, however, Vories et al. (1991) did not observe differences among three treatments with different allowable deficits.

Even with irrigation, Mid-South cotton yields fluctuate from year to year. Because much of the cropland is rented, both producers and landowners have been looking for ways to reduce yield variability, and in recent years have turned more and more to precision agriculture to improve stability. Currently available sensors can collect relatively dense georeferenced datasets of some spatially variable soil 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 soil sample collection and laboratory analysis.

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. Soil salinity, clay content, cation exchange capacity (CEC), clay mineralogy, soil pore size and distribution, and soil moisture content are some of the factors that affect EC_a (McNeill, 1992). 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 CEC (Rhoades et al., 1976).

Soil EC_a can be used to indirectly estimate specific soil properties. Kitchen et al. (1996) used direct calibration to estimate depth of flood-induced sand deposition, which could greatly affect the ability of plants to find moisture in the alluvial soils found throughout the Mid-South. Others have used EC_a to estimate the topsoil depth above a subsoil claypan horizon (Doolittle et al., 1994), which could restrict the deep rooting needed under rainfed production. Freeland et al. (2008) discussed sand blows and fissures; fissures are similar to sand blows but linear in nature. Such areas 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 might be difficult to differentiate from the surrounding soil.

Sophisticated geographic information systems (GIS) have been developed for managing and manipulating the extensive datasets created with precision agriculture (e.g., ArcMap, ESRI, Redlands, CA). As use of these programs has become more widespread, both software companies and users have prepared many subroutines for performing common tasks. Furthermore, because the high-density datasets collected with yield monitors and other instruments tend to violate some of the assumptions inherent in traditional statistical methods such as analysis of variance (ANOVA), different types of analyses are required. As the theories behind spatial statistics have become better understood, many commercial (e.g., SAS, SAS Institute, Cary, NC) and shareware (e.g., GeoDa, GeoDa Center for Geospatial Analysis and Computation, Arizona St. Univ., Tempe, AZ) software packages have been refined and developed for analyzing the large, spatially referenced datasets.

The problem of soil variability in research has been addressed traditionally by reducing plot size and assuming that the resulting experimental units were homogeneous with no spatial autocorrelation, at least within replicates. Whether through a lack of understanding or expediency, large-plot data are often analyzed with the same assumptions; however, inferences developed from ANOVA results are compromised when spatial autocorrelation is present in the data (Griffin et al., 2004). The Moran's I test statistic of the aspatial (i.e., not spatially referenced) ordinary least squares (OLS) regression residuals is a measure of spatial autocorrelation and can be interpreted as a spatial correlation coefficient (Anselin, 1988). Values range from -1 to 1, with high positive values of Moran's I interpreted as high (low) values having neighbors of high (low) values. A negative Moran's I signifies high and low value observations occur as neighbors. Site-specific yield data tend to be strongly positively spatially autocorrelated at the density at which yield monitor data are collected (Griffin et al., 2007). Furthermore, raw yield monitor data contain a variety of inherent errors and researchers have reported that 10 to 50% of the observations in a given field should be removed (Sudduth and Drummond, 2007).

Much spatially referenced information can be readily obtained at no cost from the USDA-NRCS Geospatial Data Gateway (http://datagateway.nrcs.usda.gov) and other sources. By studying information already available and supplementing it with readily obtained sensor data, it should be possible to better understand the effects of soil variability on both rainfed and irrigated production. Such knowledge will be beneficial in the optimal selection of management zones for applying site-specific crop inputs such as water and nutrients. The objective of this research was to determine the impact of soil spatial variability on both yield and irrigation water use efficiency (i.e., the increase in yield over rainfed production per unit of irrigation water applied) for cotton production.

MATERIALS AND METHODS

A field study to investigate irrigated cotton production was conducted at the Univ. Missouri Fisher Delta Research Center Marsh Farm at Portageville (36.411° N, 89.700° W) during the 2011 and 2012 growing seasons. The square field is approximately 10 ha, 320 m along either side, with the primary slope in the south to north direction. It is located roughly 14 km west of the Mississippi River and lies within the New Madrid Seismic Zone. The combination of alluvial, eolian, and seismic activity over the years has resulted in highly variable soils in the region, which can be seen in the aerial image from 1950 (Fig. 1a). Although agricultural activities during the ensuing 60 years have made the effects less obvious (Fig. 1b), they still exist.

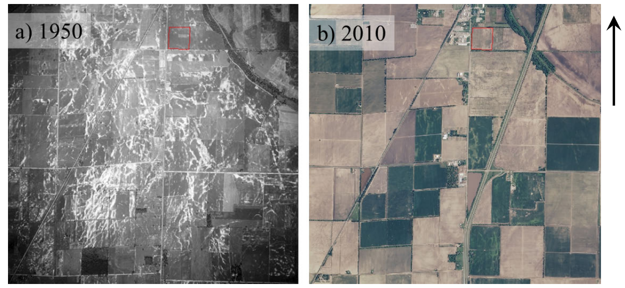


Figure 1. Aerial images of the study region from a) 1950 (US-NARA, 1951) and b) 2010 (USDA-FSA-APFO, 2010). The box in the top of the images denotes the study field.

Soil mapping units within the study field included Tiptonville silt loam (fine-silty, mixed, superactive, thermic Oxyaquic Argiudolls), Dundee sandy loam and silt loam (fine-silty, mixed, active, thermic Typic Endoaqualfs), and Reelfoot loam and sandy loam (fine-silty, mixed, superactive, thermic Aquic Argiudolls) (Fig. 2) (USDA-SCS, 1971). Soil cores collected from five locations in the field showed average sand contents ranging from 59 to 82% in the upper 0.76 m of the soil profile. As with many soils in the region, the field contains areas of high sand content such as sand blows that are often too small to show up in the soils map.

Mapping Unit	Area, ha	Average EC_a, mS m^{-1}
Dundee sandy loam (Dd)	0.1	1.89
Dundee silt loam (De)	0.7	5.18
Reelfoot loam (Re)	3.9	3.27
Reelfoot sandy loam (Rf)	4.3	2.73
Tiptonville silt loam (Tp)	1.4	4.34

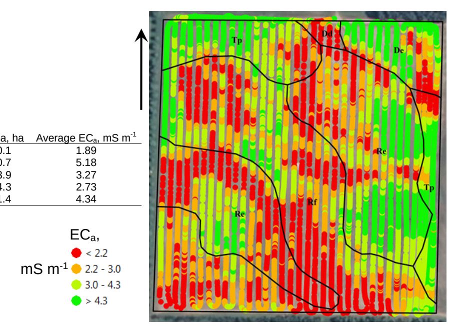


Figure 2. Study field showing soil mapping units (USDA-SCS, 1971) and EC_a values. Background is 2010 aerial image (USDA-FSA-APFO, 2010) along with the spatial soil files (USDA-NRCS, 2004).

Spatially referenced soil EC_a data were collected with a Veris 2000XA (Veris Technologies, Salina, KS) on a 1-s interval, corresponding to a 1.5 to 3-m data spacing. Measurements represented the top 0.3 m of the soil profile (Sudduth et al., 2013; Veris Technologies, 2002) and were obtained on approximately 9-m transects in the N-S direction on 22 March 2007. The sampling locations for the EC_a data were obtained by differential GPS associated with each sensor reading to provide positional information with an accuracy of 1 m or better. Elevation data were collected simultaneously with an Ashtech Z-Surveyor (Magellan Navigation, Inc., Santa Clara, CA); however, on the relatively flat soil surfaces of the region the microrelief effects that impact crop yields are not well defined with a 9-m transect and the elevation data were not included in the subsequent analyses.

The cotton cultivar PHY 375 WRF (Dow Agrosciences, Indianapolis, IN) was planted on 11 May 2011 to the east half of the field and 9 May 2012 to the west half at approximately 12 seed m^{-1} on a 97-cm row spacing on bedded soil. In both years, the previous crop was rice in the irrigated portions of the field and fallow in the rainfed corners. The crop was managed according to Univ. Missouri Extension recommendations for weed and insect control (Kendig et al., 1994). Nitrogen (N) was broadcast applied on 6 June 2011 and 22 May 2012 at 44 kg N ha^{-1} as granular urea (46% N). Three applications of urea ammonium nitrate (UAN, 32% N) at 22 kg N ha^{-1} were made each year (28 June, 6 July, 11 July 2011; 22 June, 28 June, 6 July 2012) by fertigation and therefore did not reach the rainfed portions of the field.

The crop was harvested on 5 October 2011 and 15 October 2012 with a Case IH 2155 (Case IH, Racine, WI) cotton picker equipped with an Ag Leader Insight (Ag Leader Technology, Ames, IA) yield monitor system. In 2011, the yield monitor was calibrated by placing the cotton on a trailer and weighing each load on commercial scales. In 2012, the cotton was placed in a boll buggy for transport to a module builder. Because the boll buggy was wider than the commercial scales it was not possible to weigh each sample; therefore, the yield was adjusted by a scaling factor (1.1) to match the gin records for module seed cotton weights. Yield data were “cleaned” with the Yield Editor program (v. 2.07; Sudduth et al., 2012). The Automated Yield Cleaning Expert was used and the recommended settings were fine tuned based on visual comparisons. Any erroneous data points that were still observed were manually removed. Finally, although small-plot research is typically reported in lint cotton, the yield monitor measured seed cotton and the specific gin turnouts were not available; therefore, seed cotton values were included in this report.

Because the EC_a data were collected on 9-m transects and yield data were obtained for each 97-cm row it was necessary to use either interpolation (e.g., kriging) or averaging to achieve a common density. Following the procedure set forth by Griffin et al. (2007), the more-dense yield data were assimilated with the less-dense EC_a data by creating a buffer around the EC_a data points and averaging the yield data contained within each buffer. A 1.5-m radius, slightly more than 1.5 row widths (1.45 m), was selected so that yield from three to four rows would be included in most of the yield estimates.

The field was irrigated with a 150-m Valley 8000 center pivot irrigation system (Valmont Irrigation, Valley, NE) and therefore contained rainfed areas outside the pivot. The daily SWD was estimated using the AIS. Daily ET_o was calculated using the standardized Penman-Monteith equation (ASCE-EWRI, 2004) from weather data collected at the Marsh Farm and placed on the Agricultural Electronic Bulletin Board (AgEBB; http://agebb.missouri.edu/). In 2011, two irrigation treatments (MAD1: 19-mm application at a 32-mm estimated SWD; MAD2: 25-mm application at a 44-mm estimated SWD) were assigned in a randomized complete block arrangement with three replications to approximately 30° sections of the pivot. Yield data were removed from within 25 m of the pivot point due to the small plot size at that distance. No alleys were left between plots; rather yield data were removed from 5-m sections along either side of the plot boundaries to allow for sprinkler overlap and GPS errors and to ensure that the harvest header was located completely within the plot.

Yield data collected more than 25 m beyond the final pivot drive tower were considered totally rainfed; however, in addition to the water effect, the rainfed area did not receive the fertigations (66 kg N ha^{-1} total) and had a different previous crop (fallow, versus rice for the irrigated portion). Although the likelihood of runoff from the irrigation treatments was minor, large rainfall events did induce runoff; therefore, the upslope (south) and downslope (north) portions of the field were considered position treatments in the rainfed analyses.

In 2012, a Valley Zone Control variable rate irrigation (VRI) system was installed on the center pivot allowing the inclusion of more irrigation treatments. The system included 10 independently controlled zones of approximately equal area. Approximately 30° sections of the pivot were again used, but subdivided into three plots along the length of the system, each consisting of three control zones. Six irrigation treatments (VRI settings of 0-100% in 20% increments) were assigned in a randomized complete block arrangement with three replications. A target 25-mm application at a 44-mm estimated SWD was employed and the VRI settings represented 0 to 125% of the target application in 25% increments. Zone 10 consisted of the three sprinklers on the overhang beyond the outer drive tower. The zone was set to the same VRI setting as the adjacent zone but the yield data were not included in the study. As with the yield data between the 30° sections, yield data were removed from 5 m on either side of the plot boundaries along the lateral.

The GIS program ArcMap 10.1, together with SMS Basic 14.5 (Ag Leader Technology, Ames, IA) and Excel 2010 (Microsoft, Redmond, WA) were used for managing and manipulating the extensive yield and EC_a datasets collected. Irrigation and position (rainfed) treatments were compared by creating binary dummy variables restricted to sum to zero so that the regression coefficients were interpreted as the differences from the overall mean field effect following the procedure presented by Griffin et al. (2007). Spatial-error process models were estimated using maximum likelihood with GeoDa 1.6.0 spatial analysis software for the large, spatially referenced datasets. A distance-based binary weights matrix was used to impose a neighborhood structure on the data to assess the extent of spatial autocorrelation. For each dataset, the minimum distance was selected to ensure that each observation had at least one neighbor. A spatial-error regression analysis was chosen to explicitly model the spatial autocorrelation as suggested for yield monitor data by Griffin et al. (2007).

RESULTS AND DISCUSSION

Soil. Although the soil mapping units (Fig. 2) were included in a spatial format, they were not used in the subsequent analyses. The mapping unit boundaries are based on fairly coarse sampling and during the period since the data were collected many alterations have been made to the field. Although the information is quite useful on a macro scale, it provides insufficient detail for site-specific management.

EC_a values (Fig. 2) were low, with a median value of 3.00 mS m^{-1}, mean of 3.37 mS m^{-1}, and standard deviation of 1.75 mS m^{-1}. Such low values were not surprising given the average sand contents that ranged from 59 to 82% in the upper 0.76 m of the soil profile. The patterns for the EC_a quartiles varied from the soil mapping units as expected; however, the average EC_a values for each of the mapping units were consistent with the sand axis on the soil textural triangle (i.e., sandy loam > loam > silt loam). The EC_a value associated with the yield was used as a covariate in the analyses to represent soil variability. However, given the small range of observed values, interactions with the irrigation treatments were not investigated. To avoid basing comparisons at EC_a = 0, an adjusted EC_a value was created by subtracting the field median value from each point and included as the covariate.

Weather. The 2011 and 2012 growing seasons had similar overall growing degree day accumulation but the in-season totals varied (Fig. 3). 2011 had a cooler May and September but warmer June and August. For both years, July degree day accumulations were nearly identical and within a favorable range for cotton production.

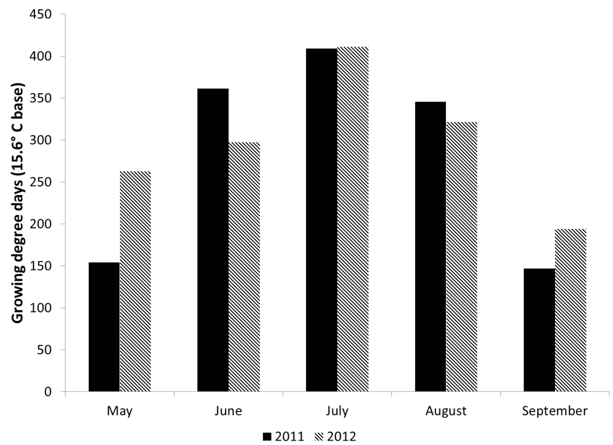


Figure 3. Growing degree days (15.6°C base) for May through September during the 2011 and 2012 growing seasons.

The 2011 and 2012 growing seasons were less similar for rainfall (Fig. 4). May 2011 had 227 mm of rainfall but most of it (157 mm) occurred before planting in the first week and probably ran off the field. 2012 was considered a drought year in much of the U.S., including the Mid-South. Whereas May and June were dryer than the previous year, July, August, and September rainfall exceeded 2011 totals. ET_o values were similar between the two seasons, although 2012 totals exceeded 2011 in each month but September.

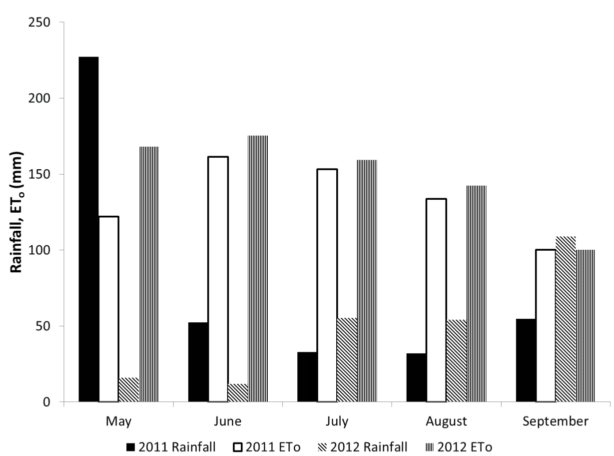
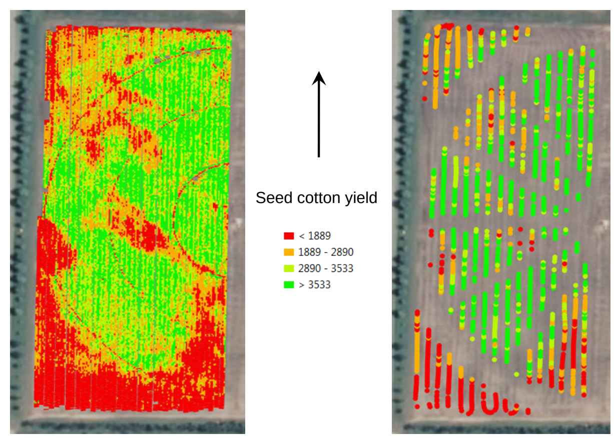


Figure 4. Rainfall and ET_o accumulations (mm) for May through September during the 2011 and 2012 growing seasons.

2011. Table 1 lists the water applications to the field from planting through 31 August. In addition to the irrigations called for by the AIS, 187 mm of rainfall was recorded and additional irrigation applications were made for herbicide and fertilizer activation and fertigation. A total of 74 mm of irrigation water was applied to all irrigated plots in addition to the scheduled irrigations. One less irrigation and an additional 7 mm of water was applied based on the higher allowable SWD (MAD2).

Figure 5 shows the yield data collected in 2011, showing a) all of the data and b) the final data set after cleaning with Yield Editor, removing data from the buffer areas around the plots, and aggregating with the EC_a data. Yield associated with each EC_a data point represented the mean of the nearest one to seven (average of 2.6) yield monitor values. As expected, the Moran's I test statistic indicated spatial autocorrelation was present in the data (Table 2). The spatial autoregressive coefficient (SAC), λ, was highly significant, suggesting that the aspatial ANOVA analysis could provide misleading results. The likelihood ratio test was highly significant ($p < 0.001$) for the spatial error model, and the standard error of regression (SER) and Akaike information criterion (AIC) were lower, indicating the spatial error model was an improvement over the OLS. Although the yield estimates did not vary greatly between the spatial and aspatial models, the probability levels were affected. Yields for the irrigation treatments were not significantly different from the mean field effect; however, the EC_a effect was significant, indicating that soil variability impacted yield more than the irrigation treatments for the two treatments imposed in 2011. The response was not surprising given that there was only one application and 7 mm of water difference.

For the rainfed portion of the field, the Moran's I test statistic again indicated spatial autocorrelation (Table 3). The SAC and the likelihood ratio test were both highly significant and the SER and AIC were lower for the spatial error model. Neither of the field positions had yields significantly different from the mean field effect, even though the difference seemed large with the downslope (wetter) position having a numerically higher yield. The EC_a effect was not significant, even though the upslope data were in an area mapped sandy loam and the downslope silt loam and the differences were supported by the EC_a data (Fig. 2).



a) SMS Basic output   b) Cleaned and aggregated to EC_a

Figure 5. 2011 seed cotton yield a) SMS Basic output and b) cleaned and aggregated to EC_a.

Table 1. Water applied to study field from 11 May planting through 31 August in 2011.

Parameter	Irrigation Treatment	
	MAD1 19-mm application @ 32-mm est. SWD[z]	MAD2 25-mm application @ 44-mm est. SWD
Total rainfall (planting-August; mm)	187	187
Number of early-season[y] irrigations	7	7
Total early-season irrigation (mm)	74	74
Number of scheduled irrigations	5	4
Total scheduled irrigation (mm)	95	102
Total irrigation application (mm)	169	176
Total water applied (planting-August; mm)	356	363

[z] Estimated soil water deficit based on Arkansas Irrigation Scheduler and locally observed weather data

[y] Early-season irrigations for herbicide and fertilizer activation, fertigation; not scheduled based on estimated soil water deficit

Table 2. Results from regression analysis (dependent variable = seed cotton yield, kg ha^{-1}) for irrigated plots in 2011.

Irrigation treatment[z]	Ordinary Least Squares			Spatial Error		
	Yield estimate (kg ha^{-1})	Standard error	*p*[y]	Yield estimate (kg ha^{-1})	Standard error	*p*
Mean field effect	3,480		< 0.001	3,410		< 0.001
MAD1	3,610	20.31	< 0.001	3,570	121.8	0.174
MAD2	3,340	20.31	< 0.001	3,240	121.8	0.174
Adjusted EC_a	383.5	19.54	< 0.001	215.5	29.44	< 0.001
λ^x				0.89	0.017	< 0.001
Degrees of freedom		1,354			1,354	
Spatial weights matrix threshold distance, m					10.6	
Measures of fit						
Standard error of regression		745			491	
Akaike information criterion		21,801			20,804	
Diagnostics tests		Value		*p*		
Moran's I (error)		0.542		< 0.001		
Likelihood ratio test		997		< 0.001		

[z] Irrigation treatments: MAD1 = 19-mm application at a 32-mm estimated SWD; MAD2 = 25-mm application at a 44-mm estimated SWD based on Arkansas Irrigation Scheduler and locally observed weather data

[y] Probability values for testing the null hypothesis H_o: value = 0, except irrigation treatment H_o: value = mean field effect

[x] λ = Spatial autoregressive coefficient

Table 3. Results from regression analysis (dependent variable = seed cotton yield, kg ha^{-1}) for rainfed plots in 2011.

Position	Ordinary Least Squares			Spatial Error		
	Yield estimate (kg ha^{-1})	Standard error	*p*[z]	Yield estimate (kg ha^{-1})	Standard error	*p*
Mean field effect	1,810		< 0.001	1,950		< 0.001
upslope	1,400	58.63	< 0.001	1,320	168.7	0.821
downslope	2,210	58.63	< 0.001	2,570	168.7	0.821
Adjusted EC_a	180.8	40.66	< 0.001	-63.9	47.79	0.181
λ^y				0.87	0.022	< 0.001
Degrees of freedom		441			441	
Spatial weights matrix threshold distance, m					9.0	
Measures of fit						
Standard error of regression		689			419	
Akaike information criterion		7,067			6,697	
Diagnostics tests		Value		*p*		
Moran's I (error)		0.585		< 0.001		
Likelihood ratio test		370		< 0.001		

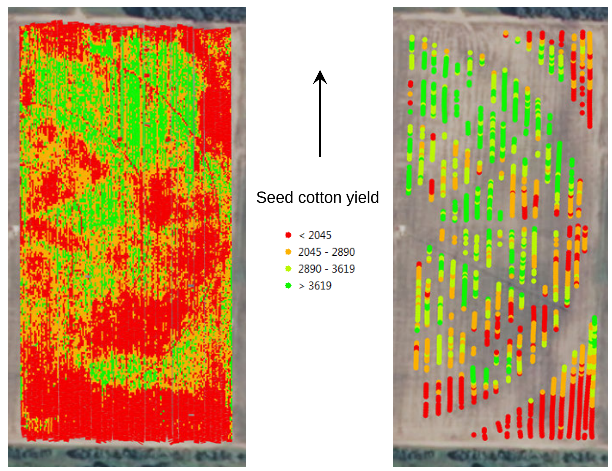
[z] Probability values for testing the null hypothesis H_o: value = 0, except irrigation treatment H_o: value = mean field effect

[y] λ = Spatial autoregressive coefficient

The mean field effect from the spatial error model for the rainfed data (1,950 kg ha^{-1}) was subtracted from the irrigated yields and used to calculate an estimated irrigation water use efficiency (IWUE; increase in yield per unit of irrigation water applied) for the irrigated treatments. The differences in previous crop and N application were confounded with the irrigation effect; however, the outer portion of the field provided the best estimate available for cotton yield without irrigation. As expected, the Moran's I test statistic indicated spatial autocorrelation (Table 4). The SAC and the likelihood ratio test were highly significant and the SER and AIC were lower for the spatial error model. Differences in estimated IWUE between either irrigation treatment and the mean field effect were not significant; however, as with yield, the EC_a effect was significant. Using a conservative gin turnout of 34%, the mean field effect estimated IWUE for lint was 0.29 kg m^{-3}, lower than the value Bordofsky et al. (1992) reported for their most efficient low energy, precision application (LEPA) treatment (0.4 kg m^{-3}) but higher than those reported by Vories et al. (2007) using furrow irrigation. The value was also higher than the 2011 values reported by Reba et al. (2014) for farmer fields located approximately 100 km from the study field.

2012. Table 5 lists the water applications to the field from planting through 31 August. In addition to the irrigations called for by the AIS, 131 mm of rainfall was recorded and additional irrigation applications were made for herbicide and fertilizer activation and fertigation. A total of 56 mm of irrigation water was applied to all irrigated plots in addition to the scheduled irrigations. Two irrigations were called for by the AIS before the installation of the VRI system was completed, resulting in a total of 34 mm of irrigation water applied to all irrigated plots. Five irrigations with the VRI system were called for by the AIS and the additional application amounts ranged from 0 to 159 mm.

Figure 6 shows the yield data collected in 2012, with a) showing all of the data and b) showing the final data set after cleaning with Yield Editor, removing data from the buffer areas around the plots, applying the scaling factor for calibration, and aggregating with the EC_a data. Yield associated with each EC_a data point represented the mean of the nearest one to 10 (average of 4.7) yield monitor values. The larger number of yield monitor values compared to 2011 resulted from a less experienced operator harvesting at a slower speed in 2012; however, the harvester was operated within the recommended range of speeds in both years. For the irrigated portion of the field, the Moran's I test statistic indicated spatial autocorrelation was present in the data as expected (Table 6). The SAC and the likelihood ratio test were both highly significant and the SER and AIC were lower for the spatial error model. With more irrigation treatments possible with the VRI system, allowing a wider range of applications, yields for four of the six treatments were significantly different from the mean field effect; however, the EC_a effect was not significant. The inclusion of a wider range of irrigation treatments appeared to negate the impact of EC_a. Although the change from the west to east half of the field was confounded in the change in irrigation treatments, both halves of the field were quite variable (Fig. 2).



a) SMS Basic output

b) Cleaned and aggregated to EC_a

Figure 6. 2012 seed cotton yield a) SMS Basic output and b) cleaned and aggregated to EC_a.

The biggest surprise in the 2012 results was that the target irrigation scheme of 25-mm applications at a 44-mm estimated SWD (100%) yielded significantly less than the mean field effect, whereas applications of 6 mm (25%) and 12 mm (50%) on the same days resulted in yields significantly greater (Table 6). Figure 7 shows the response to the different irrigation water applications associated with the treatments. Rainfall was not included in the total because it was not possible to differentiate between effective rainfall and runoff. These results contrast those of Fangmeier et al. (1989), who observed that seed cotton yields increased with the amount of water applied. However, Grimes et al. (1969) showed lint yield increased with the amount of water applied but then decreased at higher levels of applied water. Even though 2012 was considered a drought season, more rainfall was recorded in July and August than during the previous season (Fig. 4). In some years in the Mid-South, untimely rains negatively impact yields for irrigated cotton as well as other crops.

Table 4. Results from regression analysis (dependent variable = irrigation water use efficiency, kg m^{-3}) for irrigated plots in 2011.

Irrigation treatment[z]	Ordinary Least Squares			Spatial Error		
	IWUE estimate (kg m^{-3})	Standard error	p^y	IWUE estimate (kg m^{-3})	Standard error	p
Mean field effect	0.888		< 0.001	0.848		< 0.001
MAD1	0.985	0.012	< 0.001	0.960	0.070	0.104
MAD2	0.791	0.012	< 0.001	0.735	0.070	0.104
Adjusted EC_a	0.221	0.011	< 0.001	0.126	0.017	< 0.001
λ^x				0.89	0.017	< 0.001
Degrees of freedom		1,354		1,354		
Spatial weights matrix threshold distance, m				10.6		
Measures of fit						
Standard error of regression		0.428			0.284	
Akaike information criterion		1,554			569	
Diagnostics tests		Value		p		
Moran's I (error)		0.539		< 0.001		
Likelihood ratio test		985		< 0.001		

[z] Irrigation treatments: MAD1 = 19-mm application at a 32-mm estimated SWD; MAD2 = 25-mm application at a 44-mm estimated SWD based on Arkansas Irrigation Scheduler and locally observed weather data

[y] Probability values for testing the null hypothesis H_o: value = 0, except irrigation treatment H_o: value = mean field effect

[x] λ = Spatial autoregressive coefficient

Table 5. Water applied to study field from 9 May planting through 31 August in 2012.

Parameter	% of scheduled application[z]					
	0	25	50	75	100	125
Total rainfall (planting-August; mm)	131	131	131	131	131	131
Number of early-season[y] irrigations	7	7	7	7	7	7
Total early-season irrigation (mm)	56	56	56	56	56	56
Number of pre-VRI[x] scheduled irrigations	2	2	2	2	2	2
Total pre-VRI scheduled irrigation (mm)	34	34	34	34	34	34
Number of scheduled irrigations	0	5	5	5	5	5
Total scheduled irrigation (mm)	0	32	64	95	127	159
Total irrigation application (mm)	90	122	154	185	217	249
Total water applied (planting-August; mm)	221	253	285	316	348	380

[z] 100% treatment received 25-mm application when estimated soil water deficit exceeded 44 mm based on Arkansas Irrigation Scheduler and locally observed weather data; all treatments irrigated on same day

[y] Early-season irrigations for herbicide and fertilizer activation, fertigation; not scheduled based on estimated soil water deficit

[x] Pre-VRI scheduled irrigations were applied uniformly to all plots before VRI system installation was completed

Table 6. Results from regression analysis (dependent variable = seed cotton yield, kg ha^{-1}) for irrigated plots in 2012.

Irrigation treatment^{z}	Ordinary Least Squares			Spatial Error		
	Yield estimate (kg ha^{-1})	Standard error	p^{y}	Yield estimate (kg ha^{-1})	Standard error	p
Mean field effect	3,100		< 0.001	3,070		< 0.001
0	3,140	49.04	0.357	3,150	138.7	0.586
25	3,580	51.53	< 0.001	3,600	147.8	< 0.001
50	3,510	46.90	< 0.001	3,450	134.1	0.004
75	3,050	52.73	0.350	2,970	150.8	0.490
100	2,760	49.06	< 0.001	2,680	140.6	0.006
125	2,560	51.56	< 0.001	2,580	144.6	< 0.001
Adjusted EC_a	-31.61	15.46	0.041	-17.54	28.16	0.533
λ^{x}				0.83	0.012	< 0.001
Degrees of freedom		1,286			1,286	
Spatial weights matrix threshold distance, m					7.3	
Measures of fit						
Standard error of regression		793			397	
Akaike information criterion		20,941			19,466	
Diagnostics tests		Value		p		
Moran's I (error)		0.776		< 0.001		
Likelihood ratio test		1,475		< 0.001		

[z] 100% treatment received 25-mm application when estimated soil water deficit exceeded 44 mm based on Arkansas Irrigation Scheduler and locally observed weather data; all treatments irrigated on same day

[y] Probability values for testing the null hypothesis H_o: value = 0, except irrigation treatment H_o: value = mean field effect

[x] λ = Spatial autoregressive coefficient

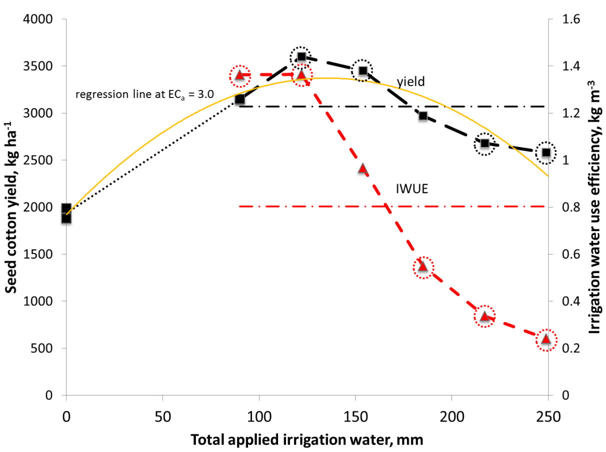


Figure 7. 2012 seed cotton yield (kg ha^{-1}) and estimated IWUE (kg m^{-3}). Horizontal lines represent mean field effect and circled points are significantly different (p < 0.05). Solid line is quadratic function for yield and EC_a calculated at the field median EC_a = 3.0 mS m^{-1}.

For the rainfed portion of the field, the Moran's I test statistic indicated spatial autocorrelation (Table 7). The SAC and the likelihood ratio test were highly significant and the SER and AIC were lower for the spatial error model. Yields for the upslope and downslope positions were numerically similar (difference of 110 kg ha^{-1} seed cotton) and not significantly different from the mean field effect; however, the probability level for the EC_a effect was 0.051, near the value of 0.05 commonly associated with significant impact even though no obvious differences in the soils were observed (Fig. 2).

As in 2011, although differences in previous crop and N application were confounded with the irrigation difference for the rainfed area, the mean field effect for the spatial error model (1,930 kg ha^{-1}) was subtracted from the irrigated yields to calculate an estimated IWUE for the irrigated treatments (Table 8). The Moran's I test statistic indicated spatial autocorrelation was present in the data, the SAC and the likelihood ratio test were highly significant, and the SER and AIC were lower for the spatial error model. Similar to yield, differences between estimated IWUE and the mean field effect were significant for five of the six irrigation treatments and the EC_a effect was not significant. The combined effect of lower yields and higher water application resulted in a steeper negative slope for estimated IWUE than for yield (Fig. 7). With six irrigation treatments, estimated IWUE was higher for some treatments and lower for others than the previous year (Table 4). The mean field effect was greater in 2011 (0.848 and 0.803 kg m^{-3} for 2011 and 2012, respectively). Again assuming a 34% gin turnout, the value for the mean field effect (0.27 kg m^{-3}) was lower than the IWUE reported by Bordofsky et al. (1992) but values for the top two treatments were higher. The mean field effect value was higher than the 2012 values reported by Reba et al. (2014) for farmer fields located approximately 100 km from the study field.

Table 7. Results from regression analysis (dependent variable = seed cotton yield, kg ha^{-1}) for rainfed plots in 2012.

Position	Ordinary Least Squares			Spatial Error		
	Yield estimate (kg ha^{-1})	Standard error	p^z	Yield estimate (kg ha^{-1})	Standard error	p
Mean field effect	1,800		< 0.001	1,930		< 0.001
Upslope	1,560	42.70	< 0.001	1,880	235.7	0.821
Downslope	2,040	42.70	< 0.001	1,990	235.7	0.821
Adjusted EC_a	275.5	22.95	< 0.001	70.65	36.18	0.051
λ^z				0.90	0.019	< 0.001
Degrees of freedom		424			424	
Spatial weights matrix threshold distance, m					8.5	
Measures of fit						
Standard error of regression		828			439	
Akaike information criterion		6,953			6,485	
Diagnostics tests		Value		p		
Moran's I (error)		0.680		< 0.001		
Likelihood ratio test		468		< 0.001		

^{z} Probability values for testing the null hypothesis H_o: value = 0, except irrigation treatment H_o: value = mean field effect

^{y} λ = Spatial autoregressive coefficient

Table 8. Results from regression analysis (dependent variable = irrigation water use efficiency, kg m^{-3}) for irrigated plots in 2012.

Irrigation treatment^z	Ordinary Least Squares			Spatial Error		
	IWUE estimate (kg m^{-3})	Standard error	p^y	IWUE estimate (kg m^{-3})	Standard error	p
Mean field effect	0.819		< 0.001	0.803		< 0.001
0	1.370	0.040	< 0.001	1.363	0.118	< 0.001
25	1.343	0.042	< 0.001	1.365	0.126	< 0.001
50	1.001	0.039	< 0.001	0.967	0.115	0.154
75	0.606	0.043	< 0.001	0.549	0.129	0.048
100	0.378	0.040	< 0.001	0.337	0.120	< 0.001
125	0.219	0.042	< 0.001	0.240	0.123	< 0.001
Adjusted EC_a	0.016	0.013	0.041	0.013	0.022	0.544
λ^x				0.85	0.010	< 0.001
Degrees of freedom	1,286			1,286		
Spatial weights matrix threshold distance, m				7.3		
Measures of fit						
Standard error of regression		0.652			0.287	
Akaike information criterion		2,571			803	
Diagnostics tests		Value	p			
Moran's I (error)		0.826	< 0.001			
Likelihood ratio test		1,768	< 0.001			

^{z} 100% treatment received 25mm application when estimated soil water deficit exceeded 44 mm based on Arkansas Irrigation Scheduler and locally observed weather data; all treatments irrigated on same day

^{y} Probability values for testing the null hypothesis H_o: value = 0, except irrigation treatment H_o: value = mean field effect

^{x} λ = Spatial autoregressive coefficient

Finally, data from the irrigated and rainfed plots in 2012 were combined for a regression analysis for seed cotton yield versus total irrigation application (Table 9). A quadratic equation was fit and the observed EC_a values were included rather than the adjusted ones. The resulting equation has a maximum of 3,372 kg ha^{-1} at 135 mm total irrigation and EC_a = 3.0 mS m^{-1}, the median observed value.

This study illustrated the importance of using appropriate spatial statistics when analyzing mapped data. For each of the yield and estimated IWUE analyses, the Moran's I test statistic indicated spatial autocorrelation was present in the data, meaning that inferences based on traditional aspatial ANOVA are compromised (Griffin et al., 2004). This was further supported in each case by other diagnostic statistics that indicated the spatial error model was an improvement over the OLS. For accurate results and inferences, it is critical that the large datasets developed with precision agriculture methods are analyzed appropriately and not automatically with the same methods and assumptions used with small-plot research.

CONCLUSIONS

Even with the recent reduction in planting, cotton is still a vital component of the economies of Mid-South states. Producers and landowners are looking for ways to reduce the variability of irrigated yields and improve the return on their irrigation investments and are turning to precision agriculture methods for assistance. EC_a is a readily obtained parameter that can indicate soil variability. Values observed in a field at the Fisher Delta Research Center in Portageville, MO, were low, with a median value of 3.00 mS m^{-1}, mean of 3.37 mS m^{-1}, and standard deviation of 1.75 mS m^{-1}, consistent with average sand contents that ranged from 59 to 82% in the upper 0.76 m of the soil profile. The average EC_a values for each of the mapping units were consistent with the sand axis on the soil textural triangle.

The 2011 and 2012 growing seasons had similar overall growing degree day accumulation but the in-season totals varied; however, both years were within a favorable range for cotton production. The growing seasons were less similar for rainfall. Although May 2011 had 227 mm of rainfall, most of it occurred in the first week and probably ran off the field. 2012 was considered a drought year and whereas May and June were dryer than the previous year, July and August rainfall exceeded 2011 totals. ET_o values were similar between the two seasons.

As expected, spatial autocorrelation was present in all of the data and thus spatial analyses were used. In 2011, the two irrigation treatments differed by only one irrigation and 7 mm of water applied. Yields for the treatments were not significantly different from the mean field effect; however, the EC_a effect was significant, indicating that soil variability impacted yield more than irrigation differences for the two treatments. For the rainfed portion of the field, yields

Table 9. Results from regression analysis (dependent variable = seed cotton yield, kg ha^{-1}) for all plots in 2012.

Irrigation treatment	Ordinary Least Squares			Spatial Error		
	Yield estimate (kg m^{-3})	Standard error	p^z	Yield estimate (kg m^{-3})	Standard error	p
Mean field effect	1,585		< 0.001	1,794		< 0.001
Irrigation total	23.19	0.783	< 0.001	21.46	2.748	< 0.001
Irrigation squared	-0.085	0.003	< 0.001	-0.079	0.011	< 0.001
EC_a	85.04	13.15	< 0.001	42.10	21.52	0.050
λ^y				0.86	0.010	< 0.001
Degrees of freedom		1,716			1,716	
Spatial weights matrix threshold distance, m					8.5	
Measures of fit						
Standard error of regression		845			420	
Akaike information criterion		28,070			26,012	
Diagnostics tests		Value	p			
Moran's I (error)		0.762	< 0.001			
Likelihood ratio test		2,058	< 0.001			

[z] Probability values for testing the null hypothesis H_o: value = 0, except irrigation treatment H_o: value = mean field effect

[y] λ = Spatial autoregressive coefficient

resulting from upslope or downslope field position were not significantly different from the mean field effect, even though the downslope (wetter) position had a numerically higher yield. The EC_a effect was not significant, even though the upslope data were in an area mapped sandy loam and the downslope silt loam. Differences in estimated IWUE between either irrigation treatment and the mean field effect were not significant; however, as with yield, the EC_a effect was significant.

In 2012, yields for four of the six irrigation treatments were significantly different from the mean field effect; however, the EC_a effect was not significant. The inclusion of a wider range of irrigation treatments appeared to negate the impact of EC_a. The target irrigation scheme of 25-mm applications at a 44-mm estimated SWD yielded significantly less than the mean field effect whereas applications of 6 and 12 mm on the same days resulted in yields significantly greater. In the Mid-South in some years, untimely rains negatively impact yields for irrigated cotton as well as other crops. For the rainfed portion of the field, yields for the upslope and downslope positions were numerically similar (difference of 110 kg ha^{-1} seed cotton) and not significantly different from the mean field effect. The probability level for the EC_a effect was approximately 0.05, the value commonly associated with significant impact, even though no obvious differences in the soils were observed. Differences between estimated IWUE and the mean field effect were significant for five of the six irrigation treatments and the EC_a effect was not significant. Estimated IWUE was higher for some treatments and lower for others than the previous year and the mean field effect was greater in 2011.

Finally, a quadratic equation was fit to the combined data from the irrigated and rainfed plots in 2012 and the observed EC_a. The resulting equation had a maximum yield of 3,372 kg ha^{-1} at 135 mm total irrigation and the median EC_a value observed in the study field (3.0 mS m^{-1}).

The next step will be to repeat these analyses on additional fields and under different environments. Larger datasets, especially for the rainfed areas, and wider ranges of EC_a values will also help to increase understanding of the impact of soil variability and increase its use it in selecting optimum management zones for site specific application of water and other inputs. Estimation of EC_a over multiple soil depths can be used to determine what depths are best for Mid-South soils and whether the optimum depth varies from field to field with the different sand features commonly encountered.

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

Allen, R.G, L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56. U.N. Food and Agriculture Organization, Rome, Italy.

Anselin, L. 1988. Spatial Econometrics: Methods and Models. Kluwer Academic Publishers, Drodrecht, The Netherlands.

American Society of Civil Engineers [ASCE-EWRI]. 2004. The ASCE standardized reference evapotranspiration equation. Technical Committee report to the Environmental and Water Resources Institute of the American Society of Civil Engineers from the Task Committee on Standardization of Reference Evapotranspiration. Amer. Soc. Civil Eng., Reston, VA.

Bordovsky, J.P., W.M. Lyle, R.J. Lascano, and D.R. Upchurch. 1992. Cotton irrigation management with LEPA systems. Trans. ASAE 35(3):879–884.

Cahoon, J., J. Ferguson, D. Edwards, and P. Tacker. 1990. A microcomputer-based irrigation scheduler for the humid mid-south region. Appl. Eng. Agric. 6(3):289–295.

Cudrak, A.J., and D.L. Reddell. 1988. A stimulus response model to predict crop yields due to water deficits. ASAE Paper No. 88-2514. Amer. Soc. Agric. Eng., St. Joseph, MI.

Doolittle, J.A., K.A. Sudduth, N.R. Kitchen, and S.J. Indorante. 1994. Estimating depths to claypans using electromagnetic induction methods. J. Soil Water Conserv. 49(6):572–575.

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. Amer. Soc. Agric. Eng., 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 [Online]. Available at: http://www.agriculture.purdue.edu/SSMC/ (verified 18 Feb 2015).

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. p. 1733-1748 *In* Proc. 7th Int. Conf. Precision Agric. Precision Resources Manag. Minneapolis, MN, 25-28 July 2004. 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.

Kendig, A., F. Fishel, and M.S. DeFelice. 1994. Cotton weed control. Agric. Ext. Bull. G4251. Univ. Missouri, Columbia, MO.

Kitchen, N.R., K.A. Sudduth, and S.T. Drummond. 1996. Mapping of sand deposition from 1993 Midwest floods with electromagnetic induction measurements. J. Soil Water Conserv. 51(4):336–340.

McNeill, J.D. 1992. Rapid, accurate mapping of soil salinity by electromagnetic ground conductivity meters. p. 209-229 *In* Advances in Measurement of Soil Physical Properties: Bringing Theory Into Practice. Spec. Pub. 30. Soil Sci. Soc. Am., Madison, WI.

Reba, M.L., T.G. Teague, and E.D. Vories. 2014. A retrospective review of cotton irrigation on a production farm in the Mid-South. J. Cotton Sci.18:137–144.

Reginato, R.J. 1983. Field quantification of crop water stress. Trans. ASAE 26(3):772–775, 781.

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. Am. Soc. Agric. Biol. Eng., St. Joseph, MI.

Sudduth, K.A., D.B. Myers, N.R. Kitchen, and S.T Drummond. 2013. Modeling soil electrical conductivity-depth relationships with data from proximal and penetrating ECa sensors. Geoderma 199:12–21.

U.S. Department Agriculture. Farm Service Agency. Aerial Photography Field Office. [USDA-FSA-APFO]. 2010. [Pemiscot Co., MO], [aerial photograph]. USDA, Washington, DC. Available at: http://datagateway.nrcs.usda.gov/). (verified 24 Feb 2015).

U.S. Department Agriculture. Natural Resource Conservation Service. [USDA-NRCS]. 2004. [Pemiscot Co., MO], Soil Survey Geographic (SSURGO) database. USDA, Washington, DC. Available at: http://datagateway.nrcs.usda.gov/). (verified 24 Feb 2015).

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

U.S. National Archives and Records Admin. [US-NARA]. 1951. [Pemiscot Co., MO], [aerial photograph]. NARA, Washington, DC.

Veris Technologies. 2002. 2000XA soil EC mapping system. Pub. #OM 1CM02-1. Veris Technologies, Salina, KS.

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.D., D.J. Pitts, and J.A. Ferguson. 1991. Response of cotton to different soil water deficits on clay soil. Irrig. Sci. 12(4):199–203.

Vories, E.D., P. Tacker, and S. Hall. 2009. The Arkansas irrigation scheduler. p. 3998–4007 *In* Proc. World Environ. Water Resources Congr. Kansas City, MI, 17-21 May, 2009. Am. Soc. Civil Eng., Reston, VA.

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.