USING NDVI FOR VARIABLE RATE COTTON IRRIGATION PRESCRIPTIONS

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HIGHLIGHTS

- Crop coefficients (K_{cb}) were calculated using Normalized Difference Vegetative Indices (NDVI) and compared to the FAO-56 method.
- Cotton yields using NDVI-K_{cb} based irrigation scheduling to a uniform checkbook irrigation were compared.
- Irrigated cotton yields were not significantly different between irrigation methods but were significantly higher in years requiring higher volumes of irrigation water.
- Cotton fiber quality was not significantly different for the two irrigation methods or plant populations.

ABSTRACT. *Irrigation timing is crucial for achieving high cotton yields and lint quality. This irrigation timing is more challenging in the southeastern U.S. Coastal Plain region due to its spatial variable sandy soils with low water and nutrient holding capacities and rainfall variability during the growing season. To address these challenges, we conducted a 2-year (2017 and 2018) study evaluating two irrigation scheduling methods under a variable rate irrigation system. The two irrigation methods were: (1) a uniform irrigation management based on weekly crop water usage, and (2) spatial crop coefficients derived from normalized difference vegetative indices (NDVI). We compared cotton yields and water use efficiency using the two irrigation scheduling methods at two different planting densities. The two plant populations were 5 and 11.5 plants m^2 to provide different NDVI readings and water requirements. In 2017, there were no significant differences in cotton yields due to the adequate rainfall during the growing season that required only three irrigations events. The mean irrigation depth for the NDVI method was significantly lower than the uniform method (56 and 64 mm, respectively, LSD = 4.2). In 2018, there was lower rainfall during the growing season requiring eight irrigation events and the cotton yields in the two irrigation treatments were significantly higher than the rainfed treatment. Irrigation depths in 2018 were not significantly different for the two irrigation methods. Water use efficiencies were not significantly different for the two irrigation methods. The planting density had little impact on the cotton yields, irrigation depth, water use efficiency, or cotton fiber quality. These results indicate that the NDVI-derived crop coefficient values were as effective in prescribing irrigation applications as the uniform irrigation method for irrigation management. The NDVI-derived crop coefficient irrigation method appears to be a useful tool for managing irrigation and developing irrigation prescriptions.*

Keywords. *Cotton, Irrigation scheduling, Normalized difference vegetation indices, Variable rate irrigation.*

Timing is crucial to achieving high yields and lint quality in cotton production; herbicide applications and management practices must be delivered or implemented at specific times to promote high lint yield and quality. This is particularly true for timing, frequency, and quantity of irrigation events, as water deficits can have detrimental effects on boll development (Schaefer et al., 2018). In the southeastern Coastal Plain of the United States, the detrimental effects of water deficits are exacerbated by two factors. First, the prevailing soil types being classified as Ultisols (Miller et al., 1983), which are predominantly sandy and have poor structure, cause low water and nutrient holding capacities that complicate crop production (Sigua et al., 2016). Secondly, rainfall in the Southeast has historically been highly variable during summer months when cotton production needs large quantities of water for vigorous growth to achieve canopy closure (Polley, 2002; Sheridan et al., 1979).

In regard to low water-holding capacity soils, states such as the Carolinas and Georgia have alleviated issues by implementing irrigation systems on a large portion of agricultural land, with South Carolina having a 500% increase in the amount of irrigated land between 1959-2012 (Templeton et al., 2017). However, cotton producers currently lack decision-support tools to aid in determining the timing and quantity of irrigation events, instead making decisions based

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upon visual assessments of the plants and soil moisture. This can result in either over- or under-watering the crop and potentially lead to other issues with crop development, pathogens, or depletion of aquifers. Research as far back as the 1990's has examined site-specific irrigation to solve issues with spatial variability in-field, whether caused by soil, microclimate, or crop species/cultivar (Sadler et al., 1996). An analysis of several case studies on site-specific irrigation also found that water conservation was increased by as much as 20% on average, per year, when incorporating the practice (Sadler et al., 2005). More recent work has been conducted to evaluate variable rate irrigation (VRI) which may further reduce the risk of over-watering (Lo et al., 2015; Sui and Yan, 2017). These studies observed increases in corn and soybean yields and minimized water stress when site-specific or VRI were implemented on a growing crop but have seen limited adoption in cotton cropping systems due to cost concerns (Bronson et al., 2006).

To provide a real-time, decision-support irrigation tool for cotton growers, several systems have been used to assess in-field cotton water deficits. These range from analog measures of leaf water potential readings with portable pressure chambers (Steger et al., 1998) to spectral vegetation indices such as the normalized difference vegetation index (NDVI; Hunsaker et al., 2005). Previous work found that NDVI was useful in determining level of crop stress (Berger et al., 2010), which suggests it may be beneficial to those wishing to rapidly assess in field issues ranging from pathogens to drought stress. The NDVI method has shown promise in determining crop water stress coefficients (K_{cb}) as a function of crop evapotranspiration (ET_c). Specific to cotton, work in the Texas high plains found that NDVI was positively correlated to lint yields and negatively correlated to water stress (Attia and Rajan, 2016). Additional research in the arid climates of Arizona (Hunsaker et al., 2005; Hunsaker et al., 2015) also observed that under adverse environmental stress conditions, NDVI was a more effective predictor of cotton stress and subsequent irrigation scheduling than simply relying on manually calculated ET_c and K_{cb} values. Recent variants such as green NDVI have also been highly correlated with leaf water potential readings (Lacerda et al., 2021). These factors, coupled with the high degree of variability that the southeastern US experiences in its seasonal rainfall (Sadler et al., 1996) indicate that NDVI may be a suitable tool for implementing more efficient irrigation scheduling in cotton in the Coastal Plain. However, this requires validation under the growing conditions found in the region.

Concerning canopy closure, water losses through soil evaporation are reduced as less direct sunlight reaches the ground, so delay of this stage can further exacerbate water stress in cotton. One of the keys to accelerating canopy closure is to manipulate planting density/plant population, which has been of interest over the last decade. In North Carolina, Riar et al. (2013) observed that greater plant populations accelerated canopy closure but did not result in greater lint yields compared to lower plant populations. Additionally, research in China showed that a moderate plant density (3.0 plants m^{-2}) achieved the best lint yields while also maintaining the lowest mean, minimum, and maximum canopy temperatures (Yang et al., 2014) compared to plant densities as low as 1.2 plants m^{-2} and as high as 5.7 plants m^{-2}. This supports the notion that canopy architecture and irrigation are closely linked, and that altering plant populations under irrigation may affect cotton yields.

Given the need for testing the efficacy of NDVI-based VRI in the southeastern Coastal Plain, the objective of this experiment was to compare cotton lint yields and water-use efficiency under NDVI-based VRI, uniform, and rain-fed irrigation at low and standard planting densities. The plant densities were used to provide a greater range of NDVI values for the NDVI-based VRI treatment.

Materials and Methods

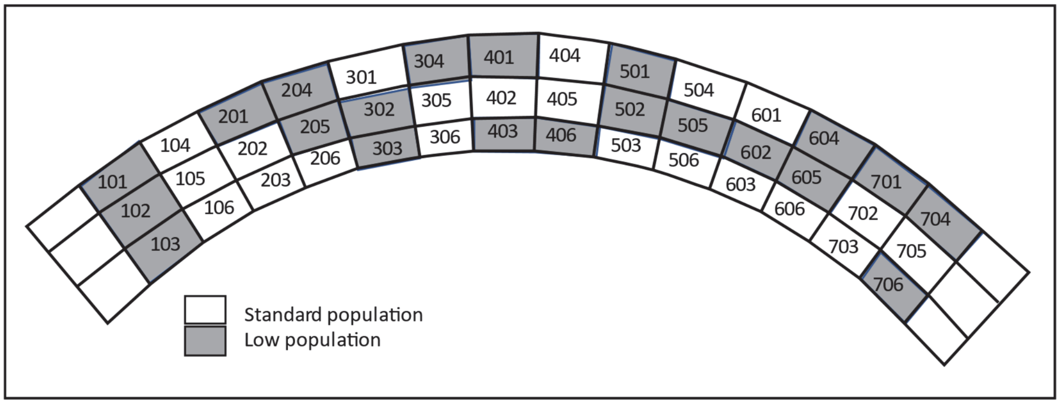
Experimental Design

This experiment was conducted in 2017 and 2018 under a 305-m long VRI system on the Clemson University Pee Dee Research and Education Center near Florence, South Carolina (34.310707° N, -79.747591° W). The 305-m VRI system had five 60-m spans, each being comprised of three 20-m management zones. Soil types under the study were Norfolk and Naboco loamy sands (0 to 2% slopes). These 20-m zones served as one of three irrigation treatments: (1) a uniform irrigation based on a weekly water usage curve (2021 Georgia Cotton Production Guide, http://www.ugacotton.com/production-guide/), (2) VRI irrigation based on calculated crop coefficients (K_{cb}) derived from NDVI measurements from individual plots, and (3) a rainfed treatment. Additionally, each 20-m zone had a planting density of either 5 seeds m^{-1} of row (low) or 11.5 seeds m^{-1} of row (Standard) to provide a greater range of NDVI measurements.

In 2017, plots were established in the three management zones under 90° of the outermost tower of the VRI system with seven replications (fig. 1). The individual plots consisted of 8 cotton rows (7.7 m) approximately 25 m long with a buffer of 7.7 m between pivot management zones and 2.5 m buffer between plots in a management zone. Due to changes in management of the VRI system in 2018, plots were established in the first 30° of the outer three towers of the VRI center pivot system with four replications (fig. 2). The individual plots were approximately 7.7 m wide and long with 10 m buffers on each side. In both years of the experiment plots were configured in a randomized complete block design.

Cotton Establishment & Management

Planting of 'Phytogen 490' cotton occurred at similar times both years, 5 May 2017, and May 9, 2018, and using a 2-row cone plot planter (Almaco, Nevada, Iowa). The plots consisted of eight 1-m wide rows and were 25 m long in 2017, and 10 m long in 2018. The plots were managed uniformly using Clemson University Extension recommendations (Jones et al., 2019) for soil fertility (90 kg N ha^{-1}, 67 kg P_2O_5 ha^{-1}, 90 kg K_2O ha^{-1} (N applied 50% preplant and 50% at 1st square), insect management [aldicarb, 2-Methyl-2-(methylthio)propanal *O*-(*N*-methylcarbamoyl) oxime], weed control [pendimethalin, 3,4-dimethyl-2,6-dinitro-*N*-



Irrigation Treatments
NDVI – 102, 104, 205, 206, 303, 306, 401, 404, 502, 503, 602, 606, 701, 702
Uniform – 103,106, 201, 203, 301, 302, 403, 405, 501, 506, 601, 605, 705, 706
Rainfed – 101, 105, 203, 204, 303, 304, 402, 406, 504, 505, 603, 604, 703, 704

Figure 1. Plot plan for the 2017 irrigation experiment using NDVI, Uniform, and rainfed treatment with two populations. The treatments were located in management zones 13-15 of the 305-m VRI system had five 60-m spans with 20-m management zone per span.

pentan-3-ylaniline; glufosinate, 2-Amino-4-[hydroxy(methylphosphonoyl)]butanoic acid], and defoliation [tribufos, 1-bis(butylsulfanyl)phosphorylsulfanylbutane]. The cotton plots were harvested on or about 15 October in both years with defoliation applied approximately 2 to 3 weeks earlier. Two rows in the center of each plot were harvested with a two-row cotton picker (John Deere 9930, Deere & Company, Moline, Ill.) equipped with an on-board weighing system (Rusty's Weigh Scales and Service, Inc., Lubbock, Tex.). Samples of seed cotton (approximately 500 g) were collected at harvest and ginned on a laboratory gin for determining lint percentage. Lint yield was calculated by multiplying the plot seed cotton weight from the weighing system by the lint percentage obtained from ginning. Ginned samples were sent to Cotton Incorporated (Cary, N.C.) for High Volume Instrument (HVI) fiber quality analysis.

Irrigation Treatments
NDVI – 101, 102, 203, 206, 304, 306, 401, 406
Uniform – 104,106, 204, 205, 303, 305, 403, 405
Rainfed – 103, 105, 201, 202, 301, 302, 402, 404

Figure 2. Plot plan for the 2018 irrigation experiment using NDVI, Uniform, and rainfed treatment with two populations. The treatments were located in management zones 7-15 of the 305-m VRI system had five 60-m spans with 20-m management zone per span.

Measurement of Water Stress Indices

To measure the soil water potentials (SWP), tensiometers (Soilmoisture Equipment Corp., Santa Barbara, Calif.) were installed in the uniform irrigation/standard-density treatment for each replication at a depth of 30 cm. These SWP readings were used to initiate irrigation events when the average SWP was below -30 kPa. When irrigation was initiated, irrigation volumes for the uniform irrigation treatment and following 3-days were based on University of Georgia recommendations. During periods of extremely high SWP reading when the tensiometers could not maintain tension, we defaulted to using the University of Georgia water use curve.

Crop reflectance was measured in the center two rows of each plot using a NDVI handheld sensor (GreenSeeker, NTech Industries, Ukiah, Calif.) to provide an averaged overall plot NDVI measurement until the plant canopy reached full closure and the NDVI values neared saturation (>0.8), after which we used the University of Georgia recommendations. The NDVI measurements were then converted into individual plot crop coefficients (K_{cb}) using the NDVI-K_{cb} relationship equation ($K_{cb} = 1.5 \times \text{NDVI} - 0.1$) developed by both Hunsaker et al. (2005) and Gonzalez-Piqueras et al. (2004). The irrigation amounts for the NDVI plots were calculated by multiplying the plot K_{cb} values by the reference evapotranspiration (ET_o). Environmental parameters were used to calculate daily reference evapotranspiration (ET_o) using the ASCE standardized equation (Allen et al., 2005), and these were collected from an on-site weather station. The irrigation volume for each irrigation event was set to the predicted crop water use for the next three days. When the SWP measurements in the uniform irrigation/standard population plots averaged below -30 kPa, an irrigation event was initiated. The uniform irrigation treatment application depth was prescribed for both the standard and low population treatments. For the NDVI treatments, the VRI application depths were based on the calculated K_{cb} values for their respective plots. Irrigation amounts for all irrigated plots were rounded to the nearest 2.54 mm (0.1 in). Finally, FAO 56 crop coefficients were also calculated to compare with our calculated NDVI K_{cb} values. The length of growth stage values used were L_{ini}= 30, L_{dev} = 50, L_{mid} = 55, and L_{late} = 45. The FAO-56 crop coefficients used were $K_{cb\ ini}$ = 0.15, $K_{cb\ mid}$ = 1.15, and $K_{cb\ end}$ = 0.5.

Statistical Analyses

Yield data, fiber quality, and water use efficiency were analyzed by analysis of variance using Proc GLM in SAS 9.4 (SAS Institute, Inc., Cary, N.C.). Irrigation method and plant density/population were fixed effects while year and replicates were random. Means were separated using a protected least significant difference.

Results and Discussion

Variable rainfall during the 2-year study period was typical for the humid Eastern Coastal Plain region (table 1). The 2017 and 2018 seasonal rainfall totals were 593 and 823 mm, respectively. The 2017 monthly rainfall totals were near the long-term monthly rainfall totals (South Carolina Climatology Office, 2021, http://www.dnr.sc.gov/climate/sco/ClimateData/cli_sc_climate.php) except for May and August that were below normal. The 2018 rainfall was below normal in June, July, and August while May, September, and October rainfall well above normal conditions. The monthly maximum and minimum temperatures were near normal during the growing season.

Irrigation was initiated when the SWP readings in the uniform irrigated treatment dropped below -30 kPa. Due to the generally adequate rainfall in 2017, the SWP readings were often above the -30 kPa level required to initiate an irrigation until late August (fig. 3). In 2017, three irrigation events were required to bring the SWP greater than -30 kPa. In

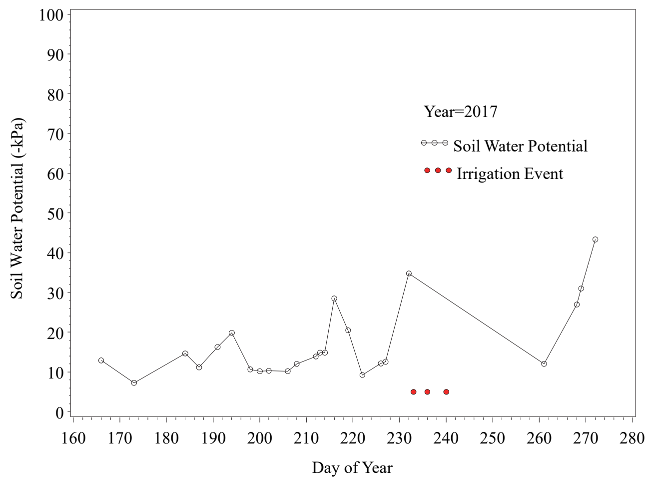


Figure 3. Averaged soil water potentials for the 2017 growing season.

2018, irrigation was required earlier and more often than in 2017 due to the below average rainfall from June through August (fig. 4). The SWP readings began decreasing in late June and dropped below -30 kPa in early July to initiate irrigation requirements. Four irrigation events were needed in July until the SWP readings increased. In mid-August the SWP readings again dropped below -30 kPa indicating the need for four more irrigation events from mid-August through early September.

Annual variation in rainfall is common in the Southeast Coastal Plain, and thus the need for irrigation is also variable. The use of soil water potential as an irrigation scheduling tool has been acknowledged as a viable system since the 1980’s (Cull et al., 1981). Because of this rapid loss of soil moisture, the continued use of soil water potential remains of value as an irrigation scheduling tool in the region. However, sandy soils of the Coastal Plain have low water capacities and dry quickly, requiring frequent rainfall or irrigation events approximately every 14 days (Busscher et al., 2006). In the present study, an SWP of -30 kPa was identified as the critical point for irrigation to be initiated, as this is the point at which plant moisture stress is generally observed in cotton (Yadvinder-Singh et al., 2014).

NDVI Measurements and K_{cb} Estimates. Observed NDVI measurements for the plots were recorded for 21 days between 15 June and 25 August in 2017 and 20 days between 29 April and 25 July in 2018. These NDVI measurements for each irrigation treatment plot were averaged and a crop coefficient was calculated for each overall NDVI irrigation treatment (table 2). The NDVI readings tended to saturate, level off, and become non-linear around 0.8 (corresponding K_{cb} = 1.1) after crop canopy closure. Thus, at this point in the season, we ceased taking NDVI measurements.

We compared our K_{cb} values to reference K_{cb} values from FAO 56. In both 2017 and 2018, our K_{cb} values followed the same trend and slope as those from FAO56. We also used the two planting populations to provide more differenced in NDVI readings in our irrigation treatments. In 2017, the calculated K_{cb} values were a few days behind the FAO 56 curve possibly due to the slower crop development with the lower rainfall after planting in May (fig. 5). Yet, it followed the FAO 56 reference line closely afterwards until the canopy

Table 1. Mean monthly maximum and minimum and cumulative monthly and total seasonal rainfall.

		Month						
		May[a]	June	July	Aug.	Sept.	Oct.	Total
2017	T max (°C)	29	30	33	31	30	25	
	T min (°C)	18	20	22	22	18	13	
	Rainfall (mm)	36	144	137	116	91	69	593
2018	T max (°C)	30	33	32	33	32	25	
	T min (°C)	20	21	21	22	21	14	
	Rainfall (mm)	137	99	103	20	321	143	823
30-year averages[b]	T max (°C)	29	32	34	33	30	25	
	T min (°C)	16	20	22	21	18	12	
	Rainfall (mm)	98	114	119	140	129	85	685

[a] Monthly rainfall for May begins at planting.
[b] 30-year monthly averages from 1991-2020 from https://www.ncei.noaa.gov/access/us-climate-normals/#dataset=normals-monthly&timeframe=30&location=SC&station=USC00383111 (accessed 6/29/2022).

Table 2. Mean NDVI values for the NDVI irrigation treatment and populations for each day NDVI data was collected.

	NDVI			NDVI	
	2017 Population			2018 Population	
Date	Standard	Low	Date	Standard	Low
6/15/2017	0.21	0.20	5/29/2018	0.24	0.23
6/22/2017	0.31	0.27	6/1/2018	0.29	0.29
6/26/2017	0.35	0.29	6/4/2018	0.28	0.28
6/30/2017	0.35	0.29	6/7/2018	0.27	0.25
7/3/2017	0.43	0.35	6/14/2018	0.39	0.34
7/6/2017	0.51	0.42	6/20/2018	0.34	0.27
7/10/2017	0.58	0.48	6/22/2018	0.45	0.35
7/13/2017	0.56	0.47	6/25/2018	0.43	0.33
7/17/2017	0.69	0.63	6/27/2018	0.60	0.50
7/19/2017	0.72	0.65	6/29/2018	0.57	0.46
7/21/2017	0.73	0.65	7/2/2018	0.60	0.46
7/25/2017	0.75	0.70	7/6/2018[a]	0.71	0.57
7/27/2017	0.72	0.67	7/9/2018	0.71	0.58
7/31/2017	0.77	0.71	7/11/2018[a]	0.74	0.59
8/2/2017	0.75	0.72	7/13/2018	0.77	0.67
8/4/2017	0.76	0.71	7/16/2018[a]	0.78	0.68
8/7/2017	0.78	0.75	7/18/2018	0.82	0.77
8/10/2017	0.81	0.78	7/20/2018	0.83	0.77
8/14/2017	0.79	0.77	7/23/2018[a]	0.82	0.76
8/21/2017[a]	0.80	0.76	7/25/2018	0.84	0.79
8/25/2017[a]	0.81	0.76			

[a] Dates when an irrigation event occurred shortly afterwards.

reached full closure for both populations. Similar results have been observed by Hunsaker et al. (2005) when comparing K_{cb} values versus reference FAO 56 values for cotton irrigation. Subsequently, they saw no difference in the amount of irrigation supplied between the FAO56 and NDVI systems and no effect on lint yield. In the present study, both planting populations followed this trend with the low population treatment lagging a few days behind the standard population treatment. This indicated that irrigation recommendations did not differ for the standard population between the FAO56 and NDVI methods, while the low population needed less water a few days later when using NDVI-based K_{cb} values.

In 2018 adequate early season rainfall resulted in the K_{cb} values being a few days ahead of the FAO 56 reference line (fig. 6). The standard population treatment continued this trend until canopy closure. After the initial few K_{cb} values, the low population treatment followed the FAO 56 line closely until measurements were discontinued. These

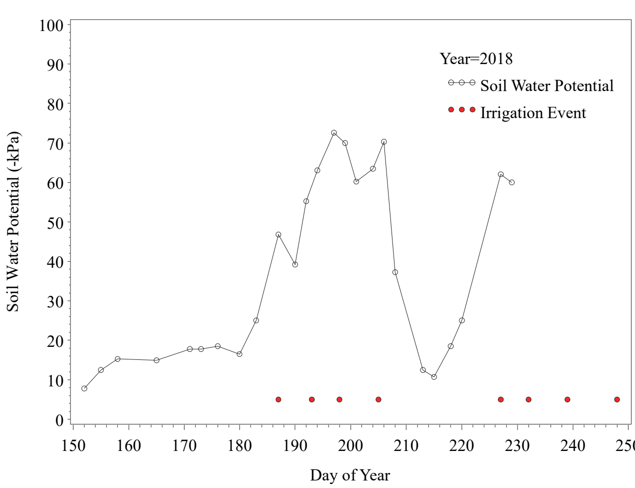


Figure 4. Average soil water potentials for the 2018 growing season.

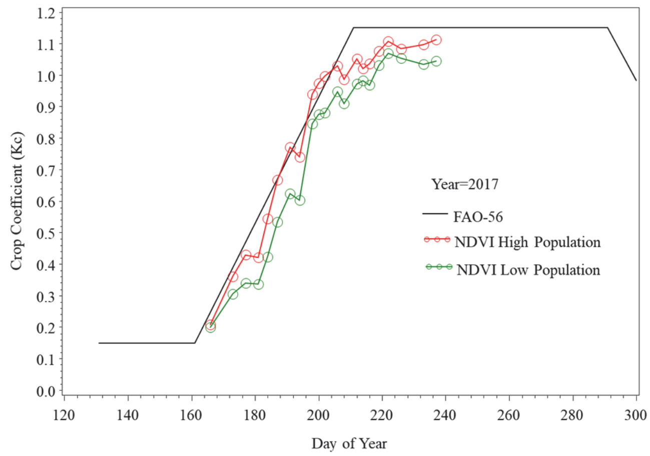


Figure 5. FAO 56 and NDVI-derived crop coefficients for cotton in 2017.

calculated K_{cb} values from the NDVI measurement can provide feedback to more closely manage irrigation applications in response to crop and environmental conditions.

In 2017, three irrigation events occurred. All uniform irrigation treatment application depths were 23 mm for the first two irrigations and 18 mm for the third irrigation. The NDVI treatment application depths ranged from 15 to 23 mm for the first two irrigations and 13 to 20 mm for the third irrigation. The NDVI standard population irrigation treatments tended to require slightly higher irrigation than the lower population treatment plots. A similar pattern was observed in 2018 with the NDVI standard population requiring greater application depths than the lower population treatments. This effect has previously been observed in corn, with lower crop densities (<3 plants m^{-2}) exhibiting less need for irrigation than normal (4.25 plants m^{-2}) or high (8.4 plants m^{-2}) planting densities (Tokatlidis et al., 2011). For the first three irrigation events in 2018, the NDVI standard population treatment required greater irrigation application depths than the Uniform irrigation treatment. After the stoppage of NDVI readings in August 2018, all following irrigation was uniformly applied to all plots.

A statistical analysis of the seasonal irrigation application depths was conducted (table 3). In 2017, the overall

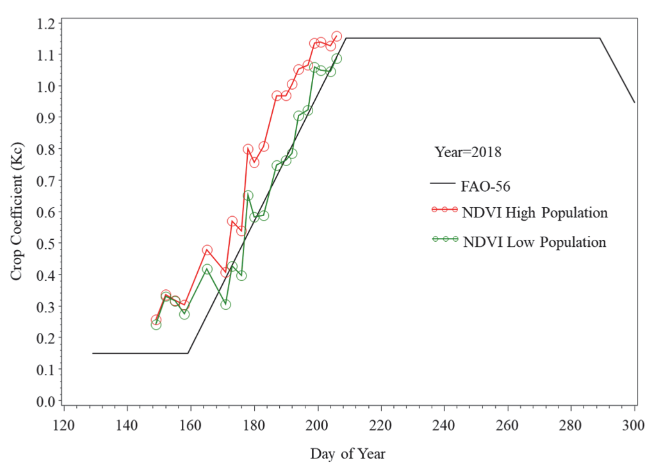


Figure 6. FAO 56 and NDVI-derived crop coefficients for cotton in 2018.

irrigation application depths across both irrigation treatments were significantly different (LSD = 4.2). The uniform irrigation treatments received greater application depths than the NDVI treatment (64 vs 56 mm). In 2018 there was no significant difference between the Uniform (168 mm) and mean NDVI (166 mm) irrigation treatments. In 2018, the NDVI standard population irrigation depths were significantly greater than the low population (LSD = 4.8), but NDVI population treatments were not significantly different from each other in 2017.

The cumulative rainfall and irrigation provided to each of the irrigation treatments are shown in figures 7 and 8. The rainfall distribution over the growing season show little rainfall in the days and weeks leading up to the irrigations. The cumulative rainfall + irrigation over the entire season shows little difference between the Uniform Irrigation and the NDVI Irrigation treatments for total water the cotton crop received in both 2017 and 2018. These results indicate that the NDVI derived K_{cb} values were as effective as the uniform irrigation method for irrigation management.

However, it is important to note that timing of rain or irrigation events can affect cotton productivity. Researchers in Brazil observed that water deficits during first flower and peak bloom stages had 40% to 50% fewer bolls and lint yield compared to plants that experienced water deficits earlier or later in the season (Zonta et al., 2017). Work in Texas has also found that application of early-season irrigation used more water and was detrimental to boll yield (Schaefer et al., 2018). In scenarios where water stress is more frequent, but not severe, NDVI could potentially detect such stress and prescribe irrigation amounts that better meet plant developmental needs than uniform irrigation while not wasting water resources.

Cotton Yields. Cotton lint and seed cotton yields were compared among the irrigation treatments for both years (table 3). The analysis for 2017 indicated that there were no significant differences in yields across the irrigation and rainfed treatments with means lint yields ranging from 1006 to 1084 kg ha^{-1} and mean seed cotton yields ranging from 2370 to 2645 kg ha^{-1}. The population irrigation treatments for both lint and seed cotton yields were not significantly different than the lower population irrigation treatments.

In 2018, the cotton lint and seed cotton yields for the uniform and NDVI irrigation treatment were significantly higher (LSD = 225 lint; LSD = 481 seed) than the rainfed

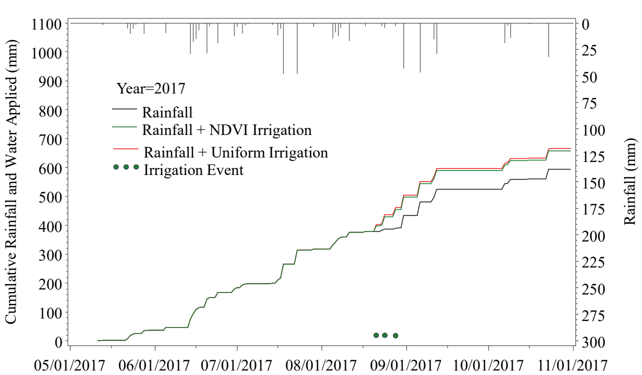


Figure 7. Cumulative rainfall and irrigation for the NDVI and Uniform irrigation treatments in 2017.

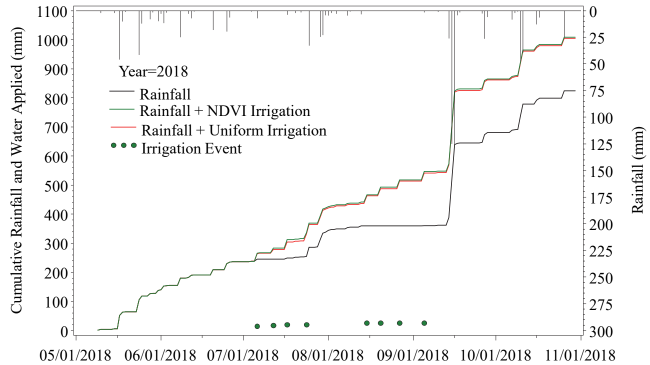


Figure 8. Cumulative rainfall and irrigation for the NDVI and Uniform irrigation treatments in 2018.

treatment with mean yields of 1318, 1274, and 957 kg ha^{-1} for the uniform, NDVI, and rainfed treatments, respectively. The overall population means between the standard and low population irrigation treatments were not significantly different. For comparison, the 2017 South Carolina State cotton lint yields for irrigated and rainfed cotton were 1210 and 907 kg ha^{-1}, respectively (USDA-NASS, https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_State_Level/South_Carolina/st45_1_0032_ 0034.pdf) and the 2018 cotton lint yields for irrigated and rainfed cotton were 1245 and 838 kg ha^{-1} (USDA-NASS, Quick Stats https://quickstats. nass.usda.gov/).

With the increase in irrigation events during 2018, these results indicated that irrigation is the primary driver of lint yield when moisture is limiting. Similar effects have been observed by Feng et al., (2014), who saw greater lint yields under successively greater irrigation amounts, but no effect from planting density under irrigation and dryland conditions in Texas. Contradictory to this, research from Mississippi has found that fixed amounts of irrigation can improve lint yields in lower populations of cotton (9.3 plants m^{-1}) compared to higher populations (12.7 plants m^{-1}) (Reddy et al., 2009). However, these findings have greater plant populations than in the present study (5 vs. 11.5 plants m^{-1}), indicating that a greater disparity in plant population may allow for greater benefits from irrigation. The cotton yield data was combined with the total irrigation treatment depths and rainfall to calculate the water use efficiency (WUE) for the irrigation and population treatments (table 4). The calculated WUE's for the lint and seed cotton were not significantly different between the irrigation or population treatment in either 2017 or 2018. The overall 2017 WUE for the lint cotton ranged from 1.6 to 1.7 kg ha^{-1} mm^{-1} and seed cotton was 4 kg ha^{-1} mm^{-1} for the irrigation treatments. The 2017 plant population WUE ranged from 1.5 to 1.8 kg ha^{-1} mm^{-1} for cotton lint and for seed cotton 3.8 to 4.3 kg ha^{-1} mm^{-1}. In 2018 the irrigation treatment lint and seed cotton WUE's ranged from 1.2 to 1.3 kg ha^{-1} mm^{-1} and 2.5 to 2.9 kg ha^{-1} mm^{-1}, respectively. The 2018 plant population WUE ranged from 1.2 to 1.3 kg ha^{-1} mm^{-1} for lint cotton and was 2.7 kg ha^{-1} mm^{-1} for seed cotton. The irrigated water used efficiency (IWUE) was calculated as the difference between the irrigated yield and rainfed yield divided by the irrigation amount. In 2017, the mean irrigation lint and seed IWUE ranged from 0.6 to 0.7 and 2.3 and 4.3 kg ha^{-1} mm^{-1},

Table 3. Mean seasonal irrigation depths and cotton lint and seed cotton yield for the irrigation and population treatments.

	Irrigation Method								Plant Population					
	2017				2018				2017			2018		
Parameter	Uniform	NDVI	Rainfed	LSD	Uniform	NDVI	Rainfed	LSD	Standard	Low	LSD	Standard	Low	LSD
Irrigation depth (mm)	64 a[a]	56b	-	4.2	168 a	166 a	-	4.8	60 a	59 a	4.2	170 a	164 b	4.8
Seed cotton yield (kg ha^{-1})	2645 a	2591 a	2370 a	460	2831 a	2757 a	2055 b	481	2689 a	2391 a	376	2561 a	2534 a	392
Lint yield (kg ha^{-1})	1044 a	1084 a	1006 a	215	1318 a	1274 a	957 b	225	1127 a	968 a	176	1195 a	1171 a	184

[a] Means with the same letter are not significantly different at $P = .05$.

Table 4. Mean water use efficiency (WUE) and irrigation water use efficiency (IWUE) for the irrigation and population treatments.

	Irrigation Method								Plant Population					
	2017				2018				2017			2018		
Parameter	Uniform	NDVI	Rainfed	LSD	Uniform	NDVI	Rainfed	LSD	Standard	Low	LSD	Standard	Low	LSD
Lint WUE (kg ha^{-1}mm^{-1})	1.6 a[a]	1.7 a	1.7 a	0.19	1.3 a	1.3 a	1.2 a	0.24	1.8 a	1.5 a	0.27	1.3 a	1.2 a	0.19
Seed cotton WUE (kg ha^{-1}mm^{-1})	4.0 a	4.0 a	4.0 a	0.89	2.9 a	2.8 a	2.5 a	0.51	4.3 a	3.8 a	0.58	2.7 a	2.7 a	0.41
Lint IWUE (kg ha^{-1}mm^{-1})	0.6 a	0.7 a	---	4.22	2.2 a	1.9 a	---	1.669	0.8 a	0.6 a	4.22	1.3 a	2.8 a	1.66
Seed cotton IWUE (kg ha^{-1}mm^{-1})	4.3 a	2.3 a	---	8.70	4.6 a	4.3 a	---	3.54	2.7 a	3.8 a	8.7	2.8 a	6.1 a	3.54

[a] Means with the same letter are not significantly different at $P = 0.05$.

respectively. The plant population lint and seed IWUE in 2017 ranged from 0.6 to 0.8 kg ha^{-1} mm^{-1} and 2.7 to 3.8 kg ha^{-1} mm^{-1}, respectively. In 2018, the plant population Lint and seed IWUE ranged from 1.4 to 2.2 kg ha^{-1} mm^{-1} and 4.3 to 4.6 kg ha^{-1} mm^{-1}, respectively.

The lack of treatment effects on WUE and IWUE are not unexpected, particularly in 2017 when irrigation events were minimal and infrequent. However, the lack of an effect from plant populations in either year were more surprising. It has been reported that higher cotton planting populations have higher IWUE than lower populations even under limited irrigation, with a limited irrigation treatment (425 mm irrigation applied) and highest populations (10.8 plants m^{-2}) having an IWUE of 13 to 15 kg ha^{-1} mm^{-1}, approximately 1.5 to 2.0 kg ha^{-1} mm^{-1} greater than the next highest combination (Chen et al., 2019). It is possible that the frequent rainfall in 2017 and the targeted irrigation amounts in 2018 were too high to illicit differences in IWUE between our treatments, given that our plant populations were similar to Chen et al., (2019). However, older research has shown no difference in IWUE between low (5.1 plants m^{-1}) and high (9.4 plants m^{-1}) cotton populations when irrigated once per season (Guinn et al., 1981). Buttar et al. (2007) have also found that cotton IWUE increased when delaying first irrigation later into the summer (42 days after sowing) and irrigating later into the season (170 days after sowing). The findings of the present study do not indicate such relationships in 2018 when irrigation was prevalent, indicating that NDVI-prescribed irrigation does not negatively affect IWUE compared to uniform or rainfed systems. The NDVI method should be assessed in the future for IWUE under more intense drought stress conditions.

Cotton fiber quality was also analyzed across irrigation treatment for all populations (table 5). There were not significant differences in micronaire across the irrigation methods or plant populations in either 2017 or 2018. The fiber length for the rainfed treatments were significantly lower than the NDVI irrigation treatment in both years, but not different than the uniform irrigation in 2017 (2017 LSD = 0.37; 2018 LSD = 0.58). The fiber strength was not significantly different in 2017, but the rainfed treatment had significantly lower fiber strength in 2018 (LSD = 1.32).

These results suggest that cotton lint micronaire is not consistently affected by irrigation, but fiber length and fiber strength appear to be greater under irrigation. These effects can be attributed to the above-average rainfall in 2017 and the near-identical amounts of Rainfed+NDVI and Rainfed+Uniform irrigation applied (figs. 5 and 6).

Similar research has noted limited or inconsistent effects of irrigation on lint quality parameters such as micronaire, fiber length, and fiber strength (Booker et al., 2006; Snowden et al., 2013). If there was more stratification between the irrigation amounts applied in the present study, there would likely be discernable differences in micronaire, and lint strength, as observed by Balkcom et al., (2006) who reported greater micronaire and fiber length values under increasing amounts of irrigation.

In summary, irrigation using NDVI-derived crop coefficients to spatially apply irrigation produced cotton yields, water use efficiencies, and fiber quality that were not significantly different than cotton uniformly irrigated. The NDVI-K_{cb} irrigation treatment method appears to be a useful tool in managing VRI irrigations systems and developing VRI prescription maps that reflect the crop development.

CONCLUSIONS

A two-year irrigation study evaluated the potential use of crop coefficients derived from NDVI field measurements was conducted in 2017 and 2018 in the humid Eastern Coastal Plain region of the United States. The study was

Table 5. Cotton fiber quality parameters.

	Irrigation Method								Plant Population					
	2017				2018				2017			2018		
Parameter	Uniform	NDVI	Rainfed	LSD	Uniform	NDVI	Rainfed	LSD	Standard	Low	LSD	Standard	Low	LSD
Micronaire	4.5 a[a]	4.6 a	4.6 a	0.17	3.9 a	3.9 a	4.0 a	0.20	4.6 a	4.5 a	0.14	4.0 a	3.9 a	0.16
Fiber length (mm)	27.9 ab	28.1 a	27.6 b	0.37	28.5 a	28.6 a	27.7 b	0.58	27.9 a	27.9 a	0.30	28.1 a	28.1 a	0.48
Fiber strength (gm/tex)	32.4 a	32.6 a	32.5 a	0.86	31.2 ab	31.9 a	30.0 b	1.32	32.4 a	32.5 a	0.70	31.2 a	30.9 a	1.07

[a] Means with the same letter are not significantly different at $P = .05$.

conducted under a variable rate irrigation (VRI) system and compared spatial NDVI-derived crop coefficient irrigation management to a uniform irrigation management based on weekly crop water use. Both the irrigation methods were planted at two plant densities to provide more variable NDVI measurements. Three irrigation events were applied in 2017 due to sufficient growing season rainfall and eight irrigation applications in 2018. The major findings of this research were:

- The calculated crop coefficients derived from NDVI field measurements paralleled those from the FAO-56 handbook.
- Only small differences in water prescriptions and application depths per irrigation event occurred in this study between NDVI crop coefficient and Uniform-based irrigation prescriptions.
- The total NDVI crop coefficient irrigation method application depths in 2017 was significantly lower than the uniform irrigation application depths while the 2018 irrigation application depths for the irrigation treatments were not significantly different. Water use efficiency and irrigated water use efficiency were not significantly different for the irrigation methods.
- Irrigated cotton yields in 2017 when few irrigations were needed were not significantly greater than rainfed cotton yields. However, in 2018 when a greater number of irrigations were required, both irrigation treatments had greater yields than the rainfed yields. Cotton fiber quality was not significantly different for the two irrigation methods or plant populations.
- NDVI appears to be a useful tool for developing dynamic irrigation prescriptions for variable rate irrigation systems. Further research under more variable crop and weather conditions is warranted.

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