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Optimizing cotton irrigation and nitrogen management using a soil water balance model and in-season nitrogen applications

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ABSTRACT

Nitrogen (N) and irrigation can be two of the costliest management inputs in United States (U.S.) cotton (*Gossypium hirsutum* L.) production systems. Furthermore, input amounts are often dependent on yearly environmental conditions, making it challenging to optimize N and irrigation management. The objectives of this research were to determine optimal N and irrigation management by: (i) evaluating equally split in-season N rates applied at first square and bloom in combination with varying levels of plant available water replacement (PAWR) estimated by an ET-based soil water balance model for cotton; and (ii) evaluate the whole-plant responses to the interaction between N and water management levels. Field experiments were conducted during 2015 and 2016 at two locations in Florida (Jay and Citra), southeastern U.S. with differing soil textures consisting of a deep sand and sandy loam. Irrigation treatments consisted of: (i) 100% of PAWR (100%); (ii) a primed acclimation (PA) treatment consisting of 50% of PAWR until first bloom and then 100% of PAWR (50% PA); (iii) 50% PAWR for the entire season (50%); (iv) a rain-fed control (RF). Nitrogen treatments consisted of even application splits at first square and bloom applied at a rate of 0 (N0), 22 (N22), 34 (N34), and 45 kg N ha^{-1} (N45). Lint yield assessments were conducted at both locations in both years. To link yield responses to possible physiological responses, in depth crop measurements consisting of SPAD chlorophyll content, leaf area index (LAI), N uptake, and harvest index (HI) were conducted at the Citra site. Contrasting soil textures and weather conditions between research locations and years allowed for a comprehensive assessment of both N and irrigation management across varying environmental conditions. Lint yield was either increased or at least maintained during the two years of this research at the Citra location by making two split N applications at first square and bloom of N22; while the optimal N treatment at the Jay location was N34 at first square and bloom in both years of this research. Additionally, a yield reduction occurred in the dry year of 2016 at the Citra location when N45 was applied at first square and bloom. The most efficient irrigation strategy at the Citra location was the primed acclimation treatment. At the Jay location, the RF control had similar lint yields as the irrigated treatments in both years, indicating that water application was not limiting at this site. These management strategies offer ways to optimize costly inputs when growing cotton in the southeastern U.S.

1. Introduction

Nitrogen is the most important applied nutrient in cotton production systems due to the potential of increasing lint yields with increasing N rates (Muharam et al., 2014). The possible economic gain by increasing N applications has led to many studies aimed at quantifying the N requirement per unit of lint produced, resulting in estimates ranging from 10 to 29 kg N 100 kg^{-1} lint across global cotton

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Abbreviations: HI, harvest index; LAI, leaf area index; PA, primed acclimation; PAWR, plant available water replenishment

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production regions (Miley and Oosterhuis, 1989; Gerik et al., 1998). Typical N application rates in the cotton production regions of the United States (U.S.) differ widely, with reported ranges from 71 to 220 kg N ha^{-1} (Taylor, 1995). A major factor adding to the complexity of determining optimal N application strategies is N loss through NO_3- leaching and denitrification, both of which are heavily influenced by unpredictable seasonal environmental conditions and soil texture.

Using in-season N applications that split the total N applied into percentages applied at varying developmental stages is a management strategy that attempts to increase N efficiency by synchronizing soil N concentrations to plant N demand. Cotton N accumulation is non-linear with an exponential increase reported to begin at first square, reaching peak accumulation rates at approximately early to mid-bloom - the developmental stage that accounts for up to 23–45% of the total N accumulation (Armstrong and Albert, 1931; Olson and Bledsoe, 1942; Bassett et al., 1970; Halevy, 1976; Oosterhuis et al., 1983; Halevy et al., 1987; Mullins and Burmester, 1991). Furthermore, N accumulation in the seeds and lint account for up to 43–60% of the total plant N, resulting in a significant amount of N accumulated in vegetative biomass during peak accumulation being remobilized relatively late in the growing season (Mullins and Burmester, 2010). Due to this late season N demand, several studies have reported lint yield increases by utilizing in-season N applications until the phenological stage characterized by peak bloom (Geng et al., 2015; Yang et al., 2011). These positive yield results may be a result of maintaining a sufficient level of N in plant vegetative biomass to serve as an N source to reproductive structures. However, the benefits of split N application are not always consistent. Some reports have observed declines in maximal obtainable lint yields when comparing split N applications of 50% at pre-plant and first square, to yields obtained by applying 100% pre-plant N, when utilizing N rates up to 180 kg N ha^{-1} (Reiter et al., 2008). Research conducted by Constable and Rochester (1988) showed that N recovery increased with making two split applications when compared to all N being applied prior to sowing. Although N recovery decreased when comparing four split applications when compared to a single pre-sowing N application. These results demonstrate that making up to two split N applications can result in a greater amount of lint produced per kilogram of N applied, translating into a greater economic return and nutrient use efficiency.

Soil properties have also been demonstrated to influence both the total in-season N rates and the timing of application. The concept of Economically Optimal Nitrogen Rate (EONR) has been found to be useful for evaluating yield responses to N applied across different soil textures which have varying levels of productivity. Scharf et al. (2012) reported a lower EONR for silt and sandy loams when compared to a clay soil. This study also found no yield differences when N was evenly split (56 kg N ha^{-1}) between pre-plant + early square or pre-plant + early flower in sand and silty loams. However, optimal N split for a clay soil was 1/3 pre-plant, 1/3 early square, and 1/3 early flower (Scharf et al., 2012). Soil texture is likely a major cause of the variability in the effectiveness of N management consisting of different total amounts or split applications. Additionally, Roberts et al. (2015) compared N mineralization and immobilization among a sandy loam and clay loam finding that the sandy loam had greater N mineralization rates. The clay loam soil texture also had greater immobilization rates when the amount of cotton residue was increased. These results demonstrate that the combination of climatic conditions and soil properties influence soil N availability over the growing season.

Irrigation water can also be a costly management input in the approximately 40% of U.S cotton production systems which receive irrigation across the southeast and southwest regions (Vellidis et al., 2016). Total water application for producing maximum lint yields in the southwest regions of the U.S. have been reported to be 74 cm; however, the relationship between lint yield and total water applied predicted lint yield reductions when total water applied was greater than 80 cm (Wanjura et al., 2002). As with N application, soil texture undoubtedly influences the lint yield responses to varying irrigation regimes (Tolk and Howell, 2010; Zhou et al., 2016). Additionally, there has been research demonstrating the sensitivity of cotton lint production to timing of water stress to specific phenological stages (Hake and Grimes, 2010). Overall, these results suggest that the effectiveness of irrigation application rates on cotton growth and yield are heavily influenced by soil type, regional and local climate conditions, and phenological development, demonstrating the need to develop irrigation scheduling solutions which encompass these variables.

Some current irrigation decision tools have begun to account for these variables and are being made readily available to growers through digital irrigation scheduling tools (Migliaccio et al., 2016; Todorovic et al., 2016). Many of these digital irrigation scheduling tools utilize soil water balance models with methods outlined in the FAO 56 Irrigation and Drainage paper (Allen et al., 1998). An irrigation scheduling tool developed specifically for cotton is the Cotton SmartIrrigation smartphone application (http://smartirrigationapps.org/cotton-app/). The model running this smart phone application is an ET-based soil water balance model that estimates root zone soil water deficits using weather data, soil parameters, crop coefficients (K_c) over plant development, and irrigation applications (Vellidis et al., 2016). The model was calibrated over multiple years and field locations by calibrating FAO 56 K_c values for cotton so that 50% root zone soil water depletion corresponded to approximately 40–50 kPa (Vellidis et al., 2016). Cotton yields were similar or greater when managing irrigation using this phone application when compared to other scheduling methods (Vellidis et al., 2016). These results indicate that this model is effective at irrigation scheduling; however more research is needed to determine if irrigation amounts can be optimized using the plant available water depletion estimates.

Individually, both N and irrigation management have been examined extensively in cotton; however, less research has examined these critical inputs simultaneously, as would be the realistic management challenge in many cotton production systems. In the small body of literature available, there is no clear indication that N and irrigation always interact. For example, Pettigrew and Zeng (2014) reported no additional gain in lint yield from furrow irrigation when N was not applied, although lint yield increases with irrigation were obtained at N rates of 56 and 112 kg N ha^{-1}. Singh et al. (2010) reported interactive effects of irrigation and in-season N management where seed cotton yield increased linearly with total N rate applications up to 200 kg N ha^{-1} with drip irrigation applied at 0.8–1.0 ET_c. This study also reported that cotton plants treated with 0.5-0.6 ET_c achieved maximal lint yields under 160 kg N ha^{-1}, with slight yield declines at 200 kg N ha^{-1}. In contrast, Bronson et al. (2006) in a study conducted in west Texas found no irrigation by N interaction when irrigation was applied using a center pivot at ET replacement rates of 63–93% and N treatments including pre-plant and split rates. Other research evaluating both N and irrigation management simultaneously has reported that lint yield was mostly determined by N when crop amount was less than 130 kg N ha^{-1}, whereas lint yields were mostly determined by plant available water when crop N was greater than this critical amount (Ockerby et al., 1993). Given these somewhat contrasting results, it is clear that cotton lint yield responses may be dependent on whether water or N availability is more limiting to lint yield.

In an effort to characterize the interaction between N and irrigation management with a focus on whole-plant responses, this study chose to assess two sites characterized by sandy/sandy loam soils. Research into these interactions is particularly important for systems with this soil texture in a humid climate because the risk for drought and N leaching losses are high, thus making management decisions regarding N and irrigation particularly impactful to economic returns and environmental quality. However, there can be a range of sandy soil textures within the southeastern U.S., so two locations were targeted for evaluation of N and irrigation management: the Jay location having a sandy loam soil texture, and the Citra location consisting of a deep sand soil texture. At both sites, the overall objectives of this research were to: (i) evaluate varying levels of plant available water replacement (PAWR) estimated by the ET-based soil water balance model Cotton SmartIrrigation smartphone application (Vellidis et al., 2016) which gives site specific recommendation for irrigation scheduling; (ii) determine optimal in-season N rates when equal split applications were made at first square and bloom; and (iii) assess the possible interactive effects of various plant available water replenish (PAWR) and in-season N rates which may influence water and N management decisions. The effectiveness of these N and irrigation treatments were evaluated by quantifying whole-plant measurements of SPAD chlorophyll content, leaf area index (LAI), N uptake, harvest index, and lint yield responses at the Citra location.

2. Materials and methods

2.1. Site characterization–Citra and Jay locations

Field studies were conducted during the years of 2015 and 2016 at two University of Florida research farm locations: 1) the Plant Science Research and Education Unit in Citra, north-central Florida (29° 24′ 38″ N, 82° 10′ 12″ W); and 2) at the North Florida Research and Education Center (NFREC) in Jay, northwest Florida (30° 46′ 31″ N, 89° 9′ 5″ W). The soil at the Citra location was classified as Candler sand (Hyperthermic, uncoated Lamellic Quartzipsamments) with an average particle size distribution of approximately 97, 2, and 2% sand, silt, clay, respectively (FSCDRS, 2018; USDA-NRCS, 2018). The average available water holding capacity for this soil texture is 0.04 cm water cm^{-1} soil with excessive drainage and very rapid permeability classifications (USDA-NRCS, 2018). The soil at the Jay location was classified as Red Bay sandy loam (Fine-loamy, kaolinitic, thermic Rhodic Kandiudults) with an average particle size distribution of approximately 65, 11, and 11% sand, silt, clay, respectively (FSCDRS, 2018; USDA-NRCS, 2018). The average available water holding capacity for this soil texture is 0.11 cm water cm^{-1} soil and is described as well-drained with moderate permeability (USDA-NRCS, 2018).

At Citra in both years, cotton (*Gossypium hirsutum* L.) was planted into a peanut (*Arachis hypogaea* L.)-cereal rye (*Secale cereal* L.)-cotton rotation. Soil preparation consisted of conventional tillage approximately five weeks before planting. Immediately prior to planting, the field was surface tilled using a field cultivator with S-tine sweeps. The cotton cultivar PhytoGen 333 WRF (Dow AgroSciences, Indianapolis, IN) was sown at a seeding density of 10–13 seeds m^{-1} with a row spacing of 0.91 m. Plots consisted of four rows 10.6 m long. The sowing was performed with a four-row vacuum planter (John Deere., Moline, IL). A soil test was conducted approximately six weeks prior to sowing, and recommended nutrients were broadcast surface applied immediately after sowing (Table 1). An even split broadcast surface application was made for potassium and sulfur recommendations which consisted of 50% at sowing + 50% at first square. At first flower, a tank mix of 0.6 kg B ha^{-1} and 0.22 kg a.i. ha^{-1} of Pyraclostrobin (BASF, Ludwigshafen, Germany) was foliar applied. Pre-emergence weed management consisted of a spray application of 1.1 kg a.i. ha^{-1} Pendimethalin (BASF, Ludwigshafen, Germany). Post-emergence weed management consisted of a spray application of 0.18 kg a.i. ha^{-1} Glyphosate and 7.9 g a.i. ha^{-1} Trifloxysulfuron.

At Jay, soil preparation consisted of conventional tillage approximately one week before sowing. Approximately 3–4 days prior to sowing, the field was tilled using a disc cultivator. The cotton cultivar, seeding density, row spacing, and row lengths were identical to those at the Citra location. Based on soil tests conducted four weeks prior to sowing, an even split broadcast surface application was made to meet the potassium recommendations which consisted of 50% at planting + 50% at first square. At first flower, 0.08 kg a.i. ha^{-1} of Pyraclostrobin and 0.05 kg a.i. ha^{-1} Metconazole (BASF, Ludwigshafen, Germany) was foliar applied. Pre-emergence weed management consisted of a spray application of 1.1 kg a.i. ha^{-1} Pendimethalin (BASF, Ludwigshafen, Germany); while post-emergence weed management consisted of two spray applications of 0.18 kg a.i. ha^{-1} Glyphosate.

2.2. Experimental design and treatments

The experimental design in both locations consisted of a split plot arrangement in a randomized complete block design. The whole plots were irrigation treatments of plant available water replacement (PAWR), or the percent water replenishment of the estimated root zone soil water deficit. These estimates were provided by the ET-based soil water balance model Cotton SmartIrrigation smartphone application (Vellidis et al., 2016; http://smartirrigationapps.org/cotton-app/). Root zone soil water availability was estimated by multiplying the rooting depth over crop development (constant across locations) by the set available water capacity (AWC) for each soil texture at each research location. The model uses an AWC of 0.06 cm water cm^{-1} soil for a sand soil texture and 0.10 cm water cm^{-1} soil for a sandy loam soil texture (Vellidis et al., 2016). Plant available water treatments consisted of: (i) 100% of PAWR (100%); (ii) a primed acclimation (PA) treatment consisting of 50% of PAWR until first bloom and then 100% of PAWR (50%PA); (iii) 50% PAWR for the entire season (50%); and (iv) a rain-fed control (RF). Irrigation was applied using a lateral move system equipped with variable rate irrigation (VRI) technology at Citra (Lindsay Corporation, Omaha, NE); while at Jay, the irrigation treatments were delivered by using a developed relationship between lateral system movement speed and irrigation amount applied (Valley Irrigation, Valley, NE). Sub-plots at both sites consisted of four in-season N treatments surface broadcast applied as NH_4NO_3 at first square and flower at 0 (N0), 22 (N22), 34 (N34), and 45 kg N ha^{-1} (N45) per application. All plots received an initial N application broadcast applied as NH_4NO_3 at 22 kg N ha^{-1} immediately after sowing.

2.3. Physiological measurements – Citra

Physiological mechanisms associated with responses to N and irrigation management were assessed at Citra through a series of whole-plant and leaf level measurements taken throughout the season. Leaf area index (LAI) was measured using an LAI-2200 (LI−COR, Lincoln, Nebraska) and was initiated at the first square phenological development stage (2015: 40 days after sowing- DAS; 2016: 37 DAS), with subsequent measurements occurring bi-weekly until 50% of plants had

Table 1

Soil properties collected prior to planting for each year and location. Soil properties represent a sampling depth from 0-0.4 m.

Year	Location	Soil pH	P kg ha^{-1}	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn	SOM g kg^{-1}	CEC cmol$_c$ kg^{-1}
2015	Citra	6.0	88	39	679	101	31	0.2	1.0	26	4.2	1.3	7	3.7
	Jay	6.5	122	186	864	189	50	0.7	1.9	17	12	3.6	21	3.1
2016	Citra	5.9	81	46	410	73	48	0.4	0.8	34	5.3	0.7	7	3.0
	Jay	6.4	25	160	1023	151	22	0.7	1.8	17	25	3.7	13	5.2

† Abbreviations P, Phosphorus; K, Potassium; Ca, Calcium; Mg, Magnesium; S, Sulfur; B, Boron; Cu, Copper; Fe, Iron; Mn, Manganese; Zn, Zinc; SOM, Soil Organic Matter assuming SOM = 1.72 x SOC; CEC, Cation Exchange Capacity.

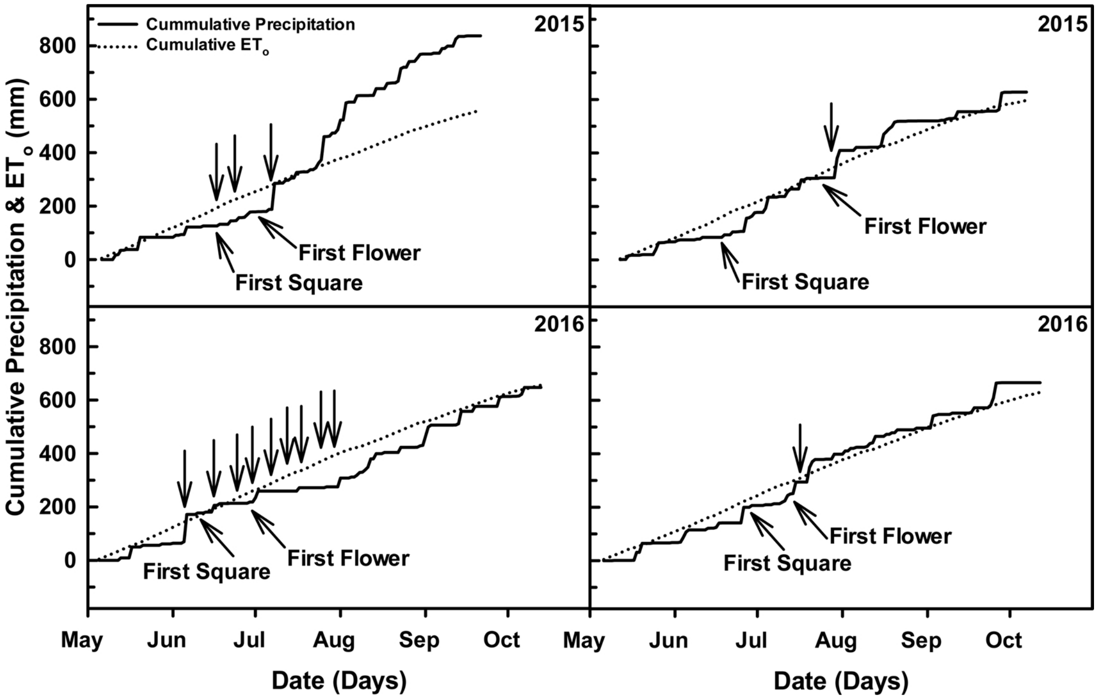

Fig. 1. Cumulative precipitation from 1 May through 1 November for 2015 and 2016 at the Plant Science Research and Education Unit (PSREU) near Citra, FL (left). Cumulative precipitation from 1 May through 1 November for 2015 and 2016 at the West Florida Research and Education Center (WFREU) near Jay, FL (right).Cumulative rainfall axis starts at planting for both years. Vertical arrows indicate when irrigation was applied.

a first fully developed boll (2015: 77 DAS; 2016: 75 DAS). A single measurement of LAI for a plot was conducted by taking one above and four equidistant readings below the canopy as a perpendicular transect between the rows with the sensor view parallel to the row and repeating this sequence with the sensor view perpendicular to the row to gain greater spatial averaging. A lens cap cover with a 45° angle was used on all measurement dates. Measurements were taken in early morning with a cast shadow over the plot area to prevent diurnal bias and underestimation of LAI values.

Leaf level measurements of SPAD chlorophyll content (Konica Minolta, Tokyo, Japan) were initiated at the first square phenological development stage with subsequent measurements occurring bi-weekly until approximately 50% of plants had a first fully developed boll. These measurements occurred on the first fully mature leaf on the main stem. Ten plants were randomly selected per plot and the measurements were averaged.

When all plots had approximately 30% of their bolls open by visual assessment, 0.75 m of row in each plot was harvested for determining N uptake. Stems were cut at the soil surface and fresh above-ground biomass per unit area was determined. Whole plants were ground using a wood chipper and approximately 500 g of fresh weight was collected as a sub-sample. This sub-sample was dried at 70 °C for seven days and weighed for determining tissue water content which was used to calculate the dry above ground biomass per unit area. The dry sub-sample was further ground through a Wiley Mill and plant material that passed through a 1 mm sieve was collected. This plant tissue was analyzed for total N (Waters Agricultural Laboratories, Inc., Camilla, GA) using the combustion method. Total percent N content was multiplied by the dry above-ground biomass per area to determine total N uptake per area.

2.4. Harvest –Citra and Jay

Termination of the cotton crop cycle was carried out when there were four nodes above the last boll that had at least partially opened. At that time, a harvest aid consisting of 0.56 kg a.i. ha^{-1} Paraquat dichloride was sprayed for defoliation. The two center rows of each plot were machine harvested using a spindle cotton picker (John Deere, Moline, IL), and lint yield determined in 2015 at 139 and 149 DAS at Citra and Jay, respectively; and in 2016 at 162 and 159 DAS at Citra and Jay, respectively. Spindle pickers were modified so cotton lint for each plot could be collected in mesh bags. Cotton lint collected was hand weighed for each plot and a 250 g sub-sample was collected and the seed removed from the lint using a table top cotton gin to determine lint yield alone (gin turnout). Harvest index was calculated as the ratio of lint weight per unit area and above-ground biomass per unit area harvested at 30% open bolls.

2.5. Statistical analysis

Statistical analysis was performed using SAS v. 9.4 statistical software (SAS Institute, 2013). PROC GLIMMIX was used to compute analysis of variance (ANOVA). Random effects of rep nested within year, and rep crossed with irrigation nested within year were included in the model. All other factors were treated as fixed. Repeated measures ANOVA was performed on measurements that were repeated over the growing season (SPAD, and LAI). Autoregressive covariance matrix structure was specified for repeated measure ANOVA. Normality and homogeneity were visually assessed by graphing the residual distribution, scatter plot of residuals, and Q-Q plot of residuals. No data was pooled over the two site years due to the strong main and interactive effect of year. Data was pooled over factors of irrigation, nitrogen, or sampling time within a season (repeated measure) when appropriate as indicated by a non-significant F-test results. Multiple comparisons significance was determined using Fisher's Protected Least Significant Difference (LSD) at a 0.05 probability level.

3. Results

3.1. Yearly precipitation and irrigation

Different amounts of precipitation were received during the two growing seasons of 2015 and 2016 at Citra; cumulative rainfall during

Table 2
Irrigation and total water received during the 2015 and 2016 growing season for each irrigation treatment at the PSREU near Citra, FL. Total water received is the sum of irrigation and precipitation.

	Irrigation Water Applied		Total Water Received	
	2015	2016	2015	2016
Irrigation Treatment	mm			
Citra Location				
100%	59	204	896	851
50%PA	46	179	883	826
50%	30	102	867	749
Rainfed	0	0	837	647
Jay Location				
100%	36	41	664	707
50%PA	36	41	664	707
50%	18	20	646	686
Rainfed	0	0	628	666

† Abbreviations: 100%, 100% PAWR per irrigation application; 50%PA, 50% PAWR per irrigation application until first flower followed by 100% PAWR per irrigation application; 50%, 50% PAWR per irrigation application for entire growing season; RF, rainfed control.

2015 and 2016 was 837 and 647 mm, respectively (Fig. 1). The varying amounts and distribution of precipitation over the growing season impacted the total number of irrigation events scheduled within the two growing seasons. During 2015, three irrigation applications were applied within the period of 41–63 DAS (Table1) for a total of 59 mm. Two of these irrigation applications occurred prior to first bloom, with the third and final application at seven days after first bloom. Following the final irrigation application the precipitation received far exceeded the reference evapotranspiration (ET_o). For 2016, there were nine irrigation applications during the period of 31–84 DAS for a total of 205 mm. Three of these applications occurred prior to first bloom, four in between first bloom and developed boll, and two in early boll development. Following the third irrigation application, the cumulative ET_o exceeded the cumulative precipitation for the majority of the rest of the growing season.

Contrary to the conditions at Citra, precipitation at Jay during 2015 and 2016 were similar. Cumulative precipitation for 2015 and 2016 were 628 and 666 mm, respectively (Fig. 1). With these levels of precipitation and the greater soil water holding capacity utilized by the soil water balance model, little irrigation was required resulting in only one irrigation treatment applied at 78 and 64 DAS during 2015 and 2016, respectively. These irrigation timings corresponded to times in phenological development when the K_c value utilized by the soil water balance was at its maximum, and when the cumulative ET_o was approximately equal to the cumulative precipitation. In both years at Jay, the cumulative ET_o did exceed cumulative precipitation early in the growing season. However, the soil water balance model did not call for irrigation. This is likely due to the combination of the greater soil water holding capacity value specified in the model and the low K_c value utilized by the model early in the phenological development.

3.2. Leaf area index and SPAD chlorophyll content

Differences in total water received during each year at Citra likely led to the differences in LAI between years (Table 2). What was similar between years was an observed trend where LAI continued to increase up to six weeks after first square (82 and 79 DAS in 2015 and 2016, respectively) to values of 4.7 and 2.9 (averaged across treatments) in 2015 and 2016, respectively (Figs. 2 and 3). Following six weeks after first square, a decrease in LAI occurred in both years, likely due to leaf senescence, to reductions of 32 and 19% in 2015 and 2016,

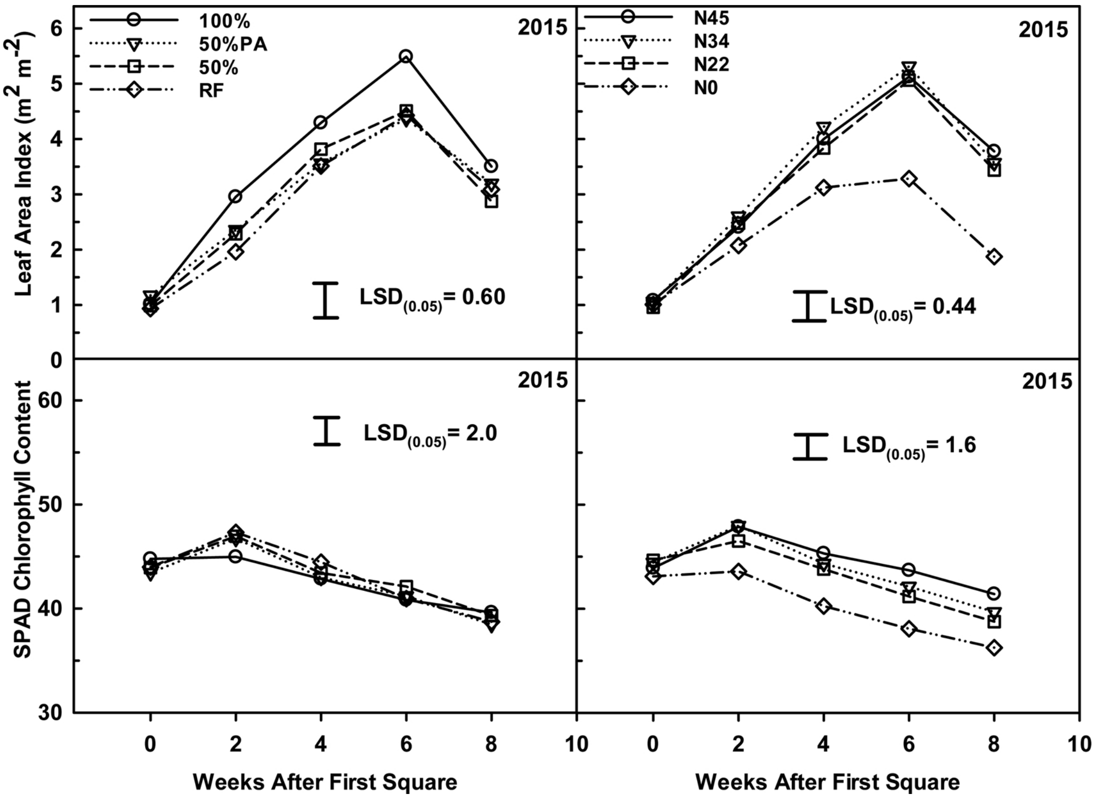

Fig. 2. Top) Average leaf area index (LAI) starting at first square and measured until 8 weeks after first square for the irrigation (left) and N treatments (right) in 2015 at PSREU. Bottom) Average SPAD chlorophyll content starting at first square and measured until 8 weeks after first square for the irrigation (left) and N treatments (right) in 2015 at PSREU (Abbreviations: 100%, 100% PAWR per irrigation application; 50%PA, 50% PAWR per irrigation application until first flower followed by 100% PAWR per irrigation application; 50%, 50% PAWR per irrigation application for entire growing season; RF, rainfed control; Nitrogen rates are uniform in-season N rates applied at first square and bloom; LSD, Fischer's Protected Least Significant Difference at $P < 0.05$).

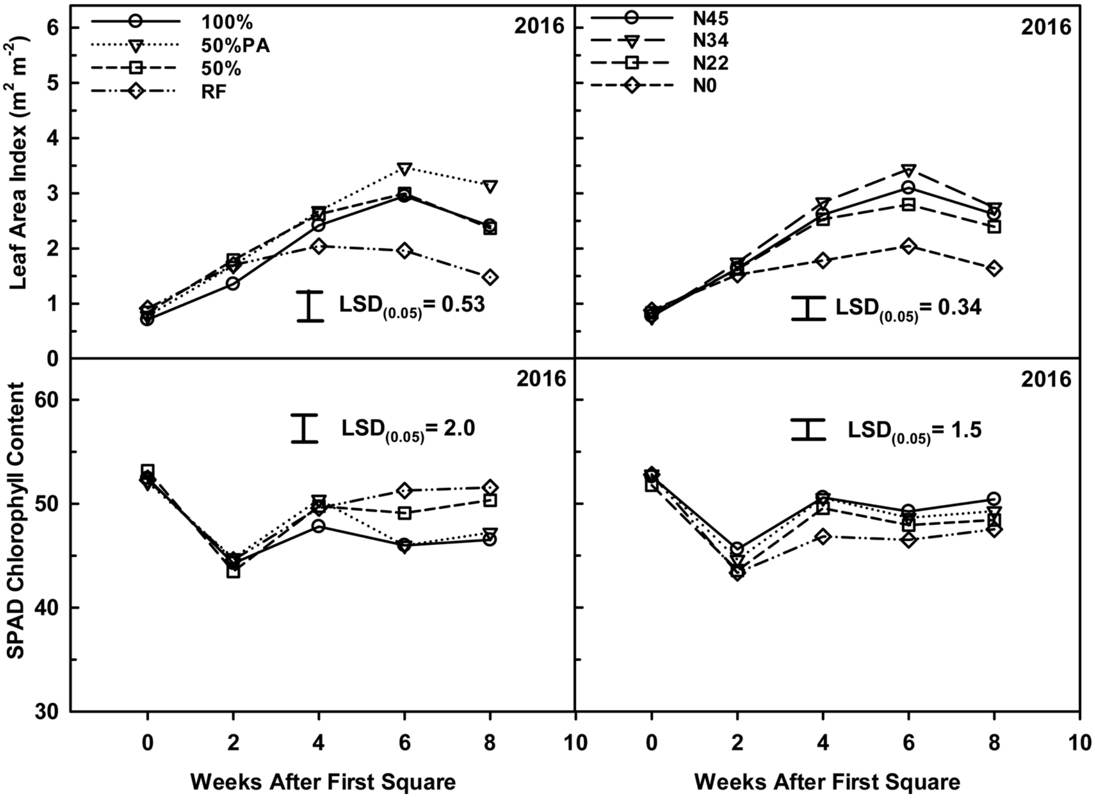

Fig. 3. Top) Average leaf area index (LAI) starting at first square and measured until 8 weeks after first square for the irrigation (left) and N treatments (right) in 2016 at PSREU. Bottom) Average SPAD chlorophyll content starting at first square and measured until 8 weeks after first square for the irrigation (left) and N treatments (right) in 2016 at PSREU (Abbreviations: 100%, 100% PAWR per irrigation application; 50%PA, 50% PAWR per irrigation application until first flower followed by 100% PAWR per irrigation application; 50%, 50% PAWR per irrigation application for entire growing season; RF, rainfed control; Nitrogen rates are uniform in-season N rates applied at first square and bloom, first square, and first bloom; LSD, Fischer's Protected Least Significant Difference at $P < 0.05$).

respectively. Year also interacted with the irrigation and N treatments: in 2015, the 100% irrigation treatment had a greater LAI than all other irrigation treatments at two weeks after first square (54 DAS) (Fig. 2). In 2016, the 50%PA treatment resulted in a greater LAI at six and eight weeks after first square when compared to the other irrigation treatments (Fig. 3). For N treatments in both years, those that received in-season N (N22, N34, and N45) maintained a greater LAI than the non-treated control following first bloom; further, these in-season N treatments maintained similar LAI across the entire season in 2015. Results were similar in 2016, except for increased LAI in the N34 treatment in comparison to the N22 treatment at six weeks following first square (79 DAS).

Differences in SPAD chlorophyll were not evident among water treatments in 2015; whereas in 2016, the RF and 50% irrigation treatments maintained greater SPAD chlorophyll content later in the growing season when compared to the 100% and 50%PA treatments (Fig. 2). In-season N rates did impact SPAD chlorophyll content in 2015 which resulted in the N22 treatment having lower chlorophyll content than the N45 at six and eight weeks after first square (82 and 96 DAP). The N45 treatment had similar SPAD chlorophyll content to the N34 treatment. In 2016, the SPAD chlorophyll content was similar among the in-season N treatments, except for the last measurement date at 8 weeks after first square (93 DAS) (Fig. 3). Overall, when averaged across all treatments, there was a lower SPAD chlorophyll content during the 2015 growing season with a marked decline after first square (40 DAS) in this year, whereas SPAD chlorophyll content was relatively stable over the measurement period in 2016.

3.3. Nitrogen uptake

There was a direct effect of N application rate on plant total N uptake in both years, with no interaction between N and irrigation (Fig. 4). A reduced amount of N uptake was observed in the treatment that only received the base application at sowing (N22) compared to all the other treatments in both years. When comparing treatments that had received in-season N, the patterns were different among years. For 2015, no differences in N uptake existed; while in 2016, the two mid-level treatments (N22 and N34) differed. When averaged across all treatments, there was an increase in N uptake of 56 kg N ha^{-1} when comparing 2016 to 2015 (Fig. 4).

3.4. Lint characteristics and harvest index

Research location had a strong impact on lint yield in both years. In 2015, greater lint yields of 1042 kg ha^{-1} were observed when comparing Jay to Citra when averaged across all treatments. Greater lint yield of 393 kg ha^{-1} were also observed at the Jay location in 2016 when averaged across all treatments. Both N and irrigation had an interactive effect with year on lint yield at the Citra location (Fig. 5), while no main or interactive effect of irrigation with N occurred for lint yields at the Jay location (Fig. 6). The variable effects of irrigation on yield noted between the sites was likely due to the fact that water was never limited at the Jay location, while water was limiting in Citra in 2016. For example, in the relatively wet year of 2015 at Citra, no lint yield differences were observed among irrigation treatments (Fig. 5); while for the relatively dry year of 2016 at this site, the 100% and 50% PA irrigation treatments had the greatest yields.

Impacts of the N treatments on lint yield were variable between the two growing season and locations. In 2015 at Citra, differences in lint yield only occurred between the N0 and N45 treatments, with the highest yield measured in the latter treatment. Similarly at Jay, a main effect of in-season N application rates was consistent among the two

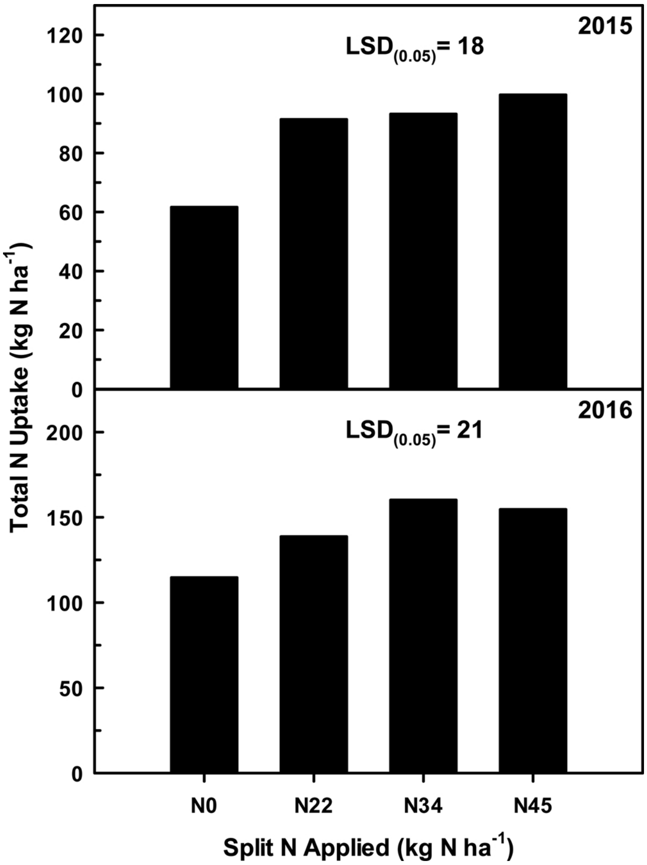

Fig. 4. Average total N uptake for each N treatment in 2015 (top) and 2016 (bottom) at the PSREU near Citra, FL. Nitrogen rates are uniform in-season rates split at first square and first bloom. Data is average over each irrigation treatment showing the N effect for each year (Abbreviations: LSD, Fischer's Protected Least Significant Difference at $P < 0.05$).

years, with the N34 and N45 treatments having similar lint yields of 1457 and 1398 kg ha^{-1}, respectively, and the N45 treatment having greater lint yield compared to the N22 treatment. Contrary to these results was the yield at Citra in 2016, with the N45 treatment having lower yield than the other three application rates.

Influences of these yield patterns were evident in the HI measured at Citra. The HI of N0 was greater than all treatments that received in-season N (N22, N34, and N45) during both growing seasons. Treatments receiving in-season N had similar HI in 2015. In 2016, the N45 treatment had a lower HI than N22.The impacts of irrigation were only evident in 2016 at this site, with a lower HI for the RF treatment when compared to 100% and 50%PA (Fig. 5). In 2015, lint yields increased with increasing N applied, despite no HI differences among the N22, N34, and N 45. This indicates that the increased lint yields from additional N application was not proportional to the increases in vegetative biomass accumulation. For 2016 at Citra, the yield and HI patterns were similar, with the highest and lowest HI values recorded for the N22 and N45 treatments, respectively (Fig. 5).

4. Discussion

One critical challenge for cotton producers that have farms with deep, sandy soils is that these soils are characterized as having low water holding capacity with rapid drainage/permeability. These soil properties can result in the development of water deficit stress from rapid soil drying during dry periods, and high amounts of nitrate leaching following intense precipitation events. These disparate events often occur in the same growing season, making irrigation and N management complex. Therefore, the use of decision support tools, such as the SmartIrrigation app tested in this study, is critically important for the efficient use of these resources in stochastic humid environment cotton production systems with high sand content soils.

The research locations and years during this research had both extremes of dry and wet conditions allowing for a broad assessment of the irrigation and N responses that are inclusive of the typical range of conditions experienced by southeastern cotton producers. The two locations of this study varied in soil texture likely contributing to differences in soil water availability among the two locations. The differences in possible soil water availability of the two soil textures is represented in the ET-based soil water balance model by having different water holding capacities. This parameter setting in combination with variability in precipitation patterns resulted in different lint yield responses to irrigation, indicating that water limitations to yield were not equal between the two locations. At Jay with soils having possibly greater soil water availability than Citra, water was clearly not limiting since in both years the RF treatment had similar lint yields when compared to the irrigated treatments. This is likely because the SmartIrrigation app scheduled only one irrigation application in both years. In this sandy loam soil type, irrigation treatments may often be more of a safeguard during years when precipitation totals are below average, but not necessarily a yearly requirement.

At the Citra location where the water holding capacity parameter utilized by the model was set at a lower value, the SmartIrrigation app scheduled a greater number of water applications in both years when compared to the Jay location. In 2016, even though similar amounts of total precipitation were received among the two locations, the irrigation scheduling tool utilized adjustments to the soil water balance model based on soil texture and precipitation timing, thus leading to a greater number of recommended irrigation events at Citra. This shows the improvement of model performance that soil texture and precipitation pattern information provides, leading to improved site specific irrigation recommendations. Even though the soils at Citra are particularly vulnerable to water deficits, the results of the current study show that a 50% reduction in PAWR can occur up until first bloom without any detriment to yield. However, when a 50% reduction in irrigation was extended past first bloom, lint yield reductions did occur when compared to 100%. Peak flower has been documented to be a sensitive time for water deficit stress due to the greatest number of young bolls being present on the plant, which are most sensitive to water deficit induced abscission (Grimes et al., 1970; Hake and Grimes, 2010).

Differences in soil texture and precipitation patterns between Citra and Jay that led to differences in the water limitations to cotton production also led to differences in the strength of N limitations at each site. This was illustrated by the differences in optimal N application rates: the optimal uniform N split application at the Jay location was N34, while the optimal rate was N22 at the Citra location. These results are contrary to the general consensus that soils with greater sand content prone to greater amounts of NO_3^- leaching require N inputs of greater quantity per application. This may be due to significant amounts of soil NO_3^- pulsing occurring during several large precipitation events early in the growing season at the Citra location in 2015, resulting in uniformly low soil N across the range of N treatments utilized in this study. This is evident in the little to no differences in SPAD, LAI, and N uptake in the wet year of 2015 at the Citra location. Furthermore, the average lint yields at Jay were substantially greater than Citra which could possibly be due to the soil texture having greater water holding capacity and nutrient fertility, but also due to less intense precipitation events resulting in large pulses of NO_3^- leaching. The overall greater lint yields at Jay also likely contributed to the lint yield responses to applying additional nitrogen with the N34 treatment, whereas the most optimal N treatment at Citra was the lower N treatment of N22.

Overall, the results in this study suggest that yearly weather

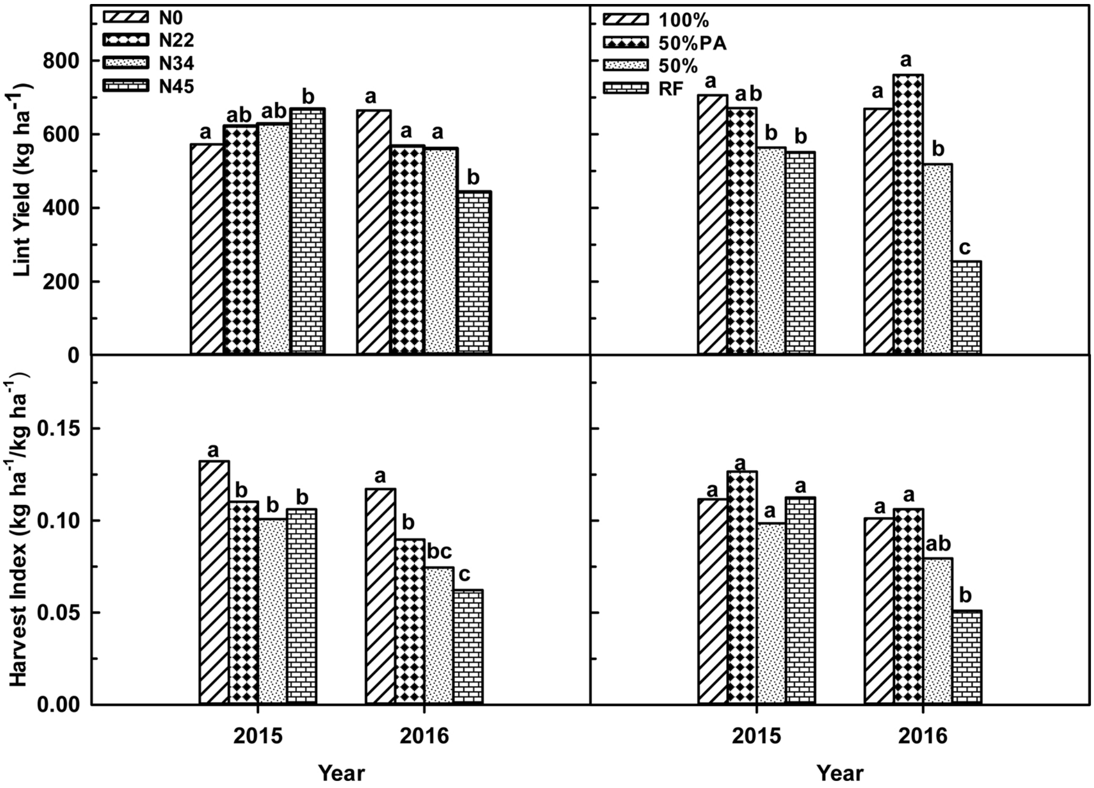

Fig. 5. Average lint yield (top) and harvest index (bottom) for each N (left) and irrigation (right) treatment in 2015 and 2016 at the PSREU near Citra, FL. Different letters indicate significance using Fischer's Protected Least Significant Difference at $P < 0.05$ (Abbreviations: Nitrogen rates are uniform in-season rates split at first square and first bloom; 100%, 100% PAWR per irrigation application; 50%PA, 50% PAWR per irrigation application until first flower followed by 100% PAWR per irrigation application; 50%, 50% PAWR per irrigation application for entire growing season; RF, rainfed control).

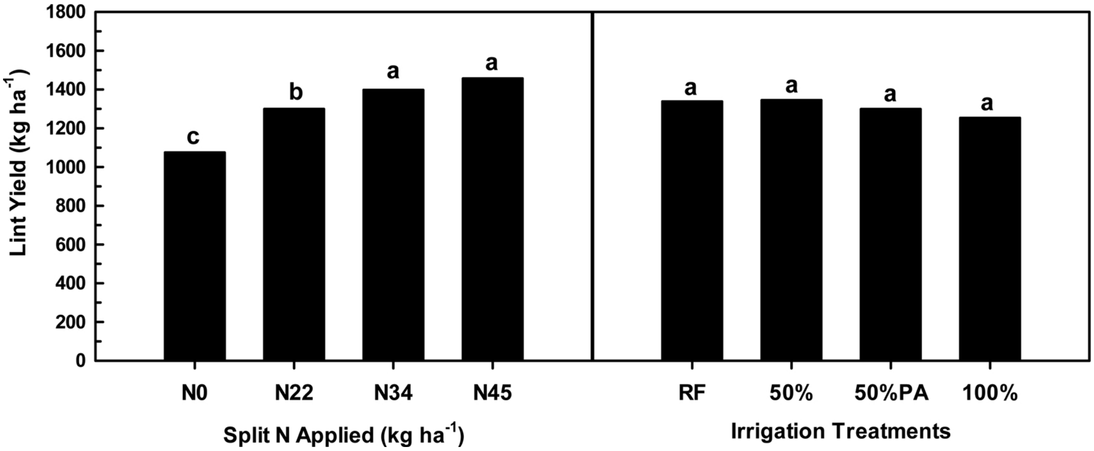

Fig. 6. Average lint yield for each N (left) and irrigation (right) treatment averaged across 2015 and 2016 at the NFREU near Jay, FL. Different letters indicate significance using Fischer's Protected Least Significant Difference at $P < 0.05$ (Abbreviations: Nitrogen rates are uniform in-season rates split at first square and first bloom; 100%, 100% PAWR per irrigation application; 50%PA, 50% PAWR per irrigation application until first flower followed by 100% PAWR per irrigation application; 50%, 50% PAWR per irrigation application for entire growing season; RF, rainfed control).

conditions determined whether N or water was more limiting to growth/yield. Further support for this conclusion is seen by the lack of an interaction between irrigation and N management on crop development and production. This result occurred despite having significant main effects of both N and irrigation during both the 2015 and 2016 growing seasons. The lack of an interaction between N and irrigation was clearly evident during the 2015 growing season, when a continual decrease in SPAD chlorophyll content in all N treatments following the last N application at first bloom (54 DAS) occurred. This indicates that all treatments receiving in-season N may have had some level of N deficiency which is also supported by the low amounts of N uptake during the 2015 season when compared to 2016. However, treatments which received N still had greater SPAD chlorophyll content and LAI than the non-treated control. Nonetheless, differences did not occur among the treatments which received in-season N for SPAD chlorophyll content, LAI, N uptake, and lint yield. These results support that in years with high precipitation and high soil NO_3^- pulsing, greater N application frequency is likely more effective than increasing the quantity of N applied in a single application.

The dry year of 2016 at Citra further underscores the point that Liebig's law of minimum, stating that the most limiting factor in a production system will limit yield, by the absence of any interaction between the N and irrigation treatments. However, in this year water was more limiting than N resulting in a strong irrigation effect. Evidence for this claim is supported by the overall reduction in LAI across all treatments when compared to the 2015 season, and larger differences in SPAD chlorophyll content, LAI, and lint yield among the irrigation treatments in 2016. Absolute values of SPAD chlorophyll content and N uptake where greater in 2016 when compared to 2015 further demonstrating that N limitation was never an issue in 2016. Other studies have documented little lint yield benefit of increasing irrigation or N when one of the other resources is limiting (Bronson et al., 2006; Pettigrew and Zeng, 2014).

The overall implications of the lack of interactive effects among irrigation and N in this study demonstrates that management of these two resources is not necessarily dependent on each other, but rather avoiding deficiency to create a synergistic effect is most critical to improving yield potentials. As demonstrated in this research, this is often a challenging task for crop producers in humid production environments with sandy soils. Therefore, technologies/tools which have early detection of water stress or N deficiency for mitigating associated yield losses is essential. The results of this research demonstrated that soil water balance irrigation scheduling tools can be beneficial in providing site-specific irrigation recommendations. However, simply basing in-season N applications on plant requirements and phenological development may not be effective strategies in environments with stochastic weather. Site-specific decision support tools for N requirements are needed for optimizing N management in stochastic agricultural production environments.

5. Conclusion

The contrasting weather conditions and soil types between the locations and years of this study allowed for a strong assessment of both N and irrigation management using smartphone irrigation support tool. In both years, lint yield maintenance or gains occurred with making two split N applications at first square and bloom of N22 at the Citra location, a 45 kg N ha^{-1} reduction in comparison to the traditional total N recommendation of 112 kg N ha^{-1}. Yield maintenance also occurred when reducing the PAWR by 50% up until first bloom. No lint yield responses to irrigation were observed in either year at the Jay location with a sandy loam soil, while the optimal uniform N split application was N34.These management strategies offer ways to cut input cost which are of economic importance when growing cotton in humid production environments with sandy or sandy loam soil types. Future research is needed that can develop tools which can give both site-specific in-season recommendation for both irrigation and N.

Acknowledgement

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