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Cotton Yield Assessment Using Plant Height Mapping System

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Abstract

Plant nitrogen status and yield potential are important factors for optimizing field management in cotton production. An experiment was conducted in 2011 at Stoneville, Mississippi to develop a method to assess plant N status and yield potential in cotton. The experimental plots were laid out in a split plot design with two irrigation treatments as main unit and six nitrogen treatments as subunit in a 10-ha cotton field. Cotton plant height was measured in real time in situ using an experimental ultrasonic device coupled with a GPS (global positioning system) receiver. Soil samples were collected and analyzed for soil residual N and soil texture before planting. Cotton leaf-blade samples were collected and analyzed for N content. Amount of water applied in irrigated treatments was recorded during the growing season. The plant height showed a quadratic relationship with yield, and this relationship was stronger in the non-irrigated plots (R2=0.60) than that in irrigated plots (R2=0.16). Irrigation had a significant effect on plant height and yield. Excess application of N did not improve cotton yield.

Keywords: cotton, plant height, ultrasonic sensor, nitrogen, irrigation

1. Introduction

Precision agriculture technologies make it possible for farmers to make site-specific adjustment of production inputs for optimal profit. Plant height is one of the key parameters to be considered in crop management. Plant height or plant growth rate can be used as an indicator of plant health status and yield potential (Sui & Thomasson, 2006; Yin, McClure, Jaja, Tyler, & Hayes, 2011; Yin, Hayes, McClure, & Savoy, 2012). With an understanding of the relationship between plant height and production-related inputs, a plant height map could be used to make site-specific adjustment of inputs such as fertilization and irrigation.

Cotton is one of the major agricultural crops in the world and is the most popular natural fiber for clothing and textile products. Nitrogen fertilization is an important field practice for cotton crops. During the growing season, cotton plants must receive appropriate rates of nitrogen (N) fertilizer for optimal yield and quality. Under-fertilization or over-fertilization of N can negatively affect desired growth patterns of cotton plants and thus degrade fiber quality and reduce yield (Fernandez, McInnes, & Cothren, 1996; Gerik, Oosterhuis, & Torbert, 1998). Additionally, over-fertilization with N will increase production costs while increasing the potential for negative environmental impacts (Bakhsh et al., 2002; USEPA, 2003). In conventional N management systems, N fertilizer is uniformly applied across a field. However, due to spatial variability of soil properties in the field, plants in some parts of the field may need more N while plants in other parts may require less. It is desirable to diagnose N status of plants in individual locations within the field and site-specifically apply appropriate amount of N that the plants need.

As with other crops, cotton plants require the proper amount of water for desirable growth, and water application is another critical component in cotton production. The Mid-South of the U.S. is one of the major areas in the country in cotton production. In this region average annual rainfall is around 1270 mm, however, precipitation patterns frequently include heavy precipitation events that increase runoff from cropland with only a small amount of rainfall entering into the soil profile (UCS, 2011). Runoff coupled with nutrient leaching has become an environmental concern (Goolsby & Battaglin, 2001). Uncertainty in the amount and timing of precipitation is one of the most serious risks to producers, and highly variable soil textural characteristics of the region require careful irrigation planning. In recent years, cotton producers have become increasingly reliant on supplemental irrigation during dry periods to ensure adequate yields and reduce risks of production. There is a need to provide technical tools to the cotton producers for appropriate management of irrigation and nutrient application.

Ultrasonic technology allows measurement of distance by transmitting a series of ultrasonic pulses through an ultrasonic transducer toward an object at the speed of sound, then waiting for the echo to return from the object. The distance between the sensor and the object can be calculated based on the speed of sound and the elapsed time between ultrasonic pulse transmission and echo return. Ultrasonic sensing devices have been developed and evaluated for measuring plant morphological characteristics such as plant height, structure, and biomass (Sui, Wilkerson, Wilhelm, & Tompkins, 1989; Tumbo, Salyani, Whitney, Wheaton, & Miller, 2002; Aziz, Steward, Birrell, Shrestha, & Kaspar, 2004; Gil, Escola, Rosell, Planas, & Val, 2007). The ability to rapidly and conveniently map plant height over time may allow for diagnosing plant stresses and optimizing production inputs in precision agriculture practices (Scotford & Miller, 2004). Jones, Maness, Stone, and Jayasekara (2004) estimated plant biomass using the product of top view surface area of the plant and plant height resolved through ultrasonic distance sensing. Sui and Thomasson (2005) developed an ultrasonic plant height mapping system. Preliminary test of the system in a non-irrigated cotton field was conducted, and it was found the plant height measured using the system showed a good relationship with leaf N content and yield. In another study by Sui and Thomasson (2006), cotton plant height was used as an input with plant canopy reflectance to train an artificial neural network for diagnosing cotton plant N status.

Objectives of this study were to 1) evaluate field performance of an ultrasonic plant height mapping system; 2) assess the relationships among plant height, leaf-blade N content, and yield in cotton; and 3) test the effect of irrigation on cotton plant height, leaf-blade N, and yield.

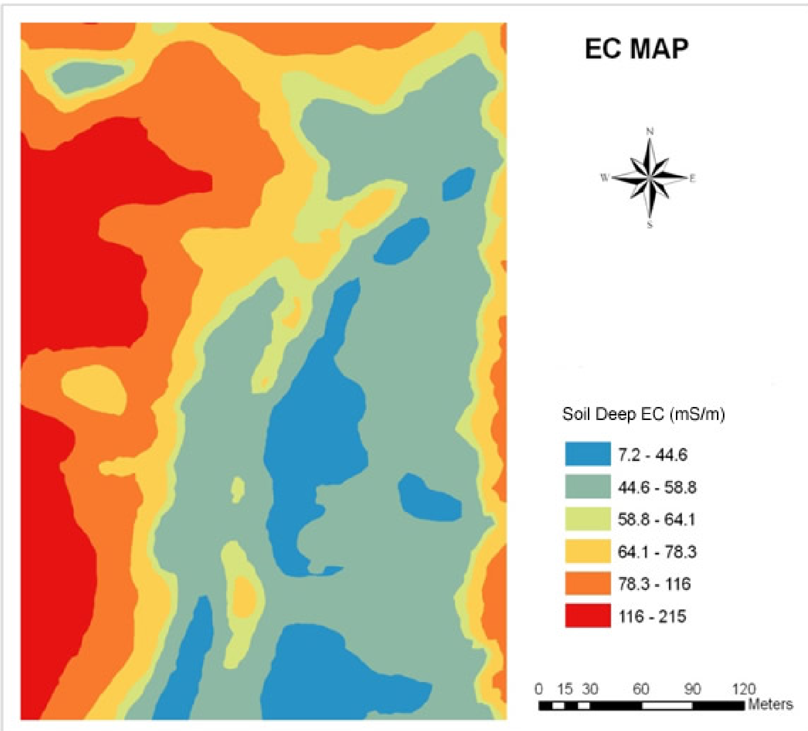

Figure 1. Soil EC map of the experimental field

2. Material and Methods

2.1 Experimental Plots

A 10-ha cotton field at USDA-ARS Crop Production Systems Research Unit farm in Stoneville, MS (latitude: 33°26'30.86", longitude: -90°53'26.60") was selected as an experimental site. There was an approximately 0.5% slope from the east side of the field to the west. Soil texture of the field varied from silt to silt loam. In general, the western half of the field had a higher soil electrical conductivity (EC) than the east half (Figure 1). Based on a soil EC map and with consideration of soil texture, experimental plots were laid out in a split plot design with 2 irrigation treatments (irrigated and non-irrigated) as the main unit and 6 nitrogen treatments (0, 39, 67, 101, 135, and 168 kg/ha) as the subunit. The main unit design was randomized complete block (RCB) with 2 blocks. There were 2 replications (blocked) of the subunit within each main unit (Figure 2). This resulted in 12 plots in each block and 48 plots in total in the field. Southwest and Northeast parts of the field were assigned as the irrigated blocks while the Southeast and Northwest parts as non-irrigated. One N application rate was randomly assigned to each plot, which was 48.8 m long, 23.2 m wide, with 24 rows in each plot. In order to prevent water from the irrigated blocks running into non-irrigated plots, a levee barrier was formed using soil along the west edge of the irrigated blocks. A 7.7 m-wide buffer was used between the plots. One soil sample from each plot was collected before planting and analyzed for residual N and texture property at the Mississippi State University Extension Service Soil Testing Laboratory in Starkville, MS.

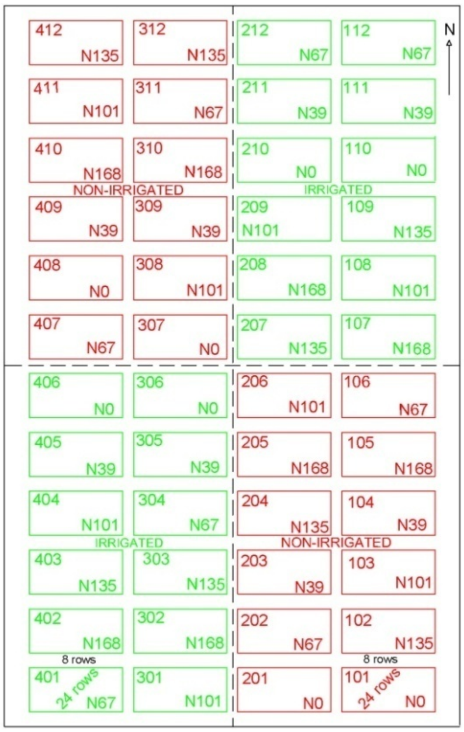

Figure 2. Experimental plot layout in a 10-ha cotton field

A glyphosate-resistant cotton cultivar (DP 0912 B2RF) (Monsanto, St. Louis, MO) was planted on May 8, 2011 with a row spacing of 0.97 m. N in the designated rate was applied to each plot using a side knife drill on June 24, 2011. Irrigation water was applied to alternate furrows using a poly-pipe system. The irrigated plots were irrigated twice during the season based on soil water content measured using soil moisture sensors: 5 cm of water was applied on July 6, 2011 and 7.6cm on July 20, 2011.

2.2 Plant Height Mapping System

A prototype ultrasonic sensing system was developed, and consisted of an ultrasonic sensor, a GPS (global positioning system) receiver, and a data acquisition unit. The ultrasonic transducer was driven by an ultrasonic ranging module (Ultra-SR, Senix Corporation, Bristol, VT). When the ranging module was triggered by an initiation signal, it generated a set of pulses and sent them to the ultrasonic transducer. A set of ultrasonic pulses were then transmitted toward the plant canopy at the speed of sound, approximately 350 meters per second. When the first ultrasonic pulse echoed back from the plant canopy to the sensor, the ranging module detected the returning echo. The difference in time between initial and echo signal is a measure of the distance from the ultrasonic sensor to the plant canopy, and plant height was calculated by subtracting the measured distance from the distance between the ground and the sensor. Beam angle of the sensor was 12 degree. The ranging module included a serial data connection which was used to connect the ultrasonic system to a data acquisition device to collect and display the ultrasonic sensor measurements (Sui & Thomasson, 2006).

The data acquisition unit was a single board computer (SBC)-based system (RLC-ARM, RLC Enterprises, Inc., Paso Robles, CA) with a touch screen for collecting the data from the ultrasonic sensor and GPS receiver. The data acquisition unit consisted of a 206 MHz, 32-bit, low-power CPU and a complete set of Windows CE compatible peripherals suitable for embedded low-power and battery applications. The system contained two serial ports and a PCMCIA controller for memory cards. The digital signal from the ultrasonic distance measurement module was read by the SBC through one of its serial ports. The other serial port was employed to record spatial information from a GPS receiver in real time so that a plant height map could be made. Plant height and spatial information were displayed on a color screen and stored in a PCMCIA memory card. The entire data acquisition system was powered by a 12-volt battery. Embedded Visual Basic was used as the programming language for the system operation code (Sui & Thomasson, 2005).

2.3 Data Collection and Analysis

The ultrasonic sensor was mounted facing down toward the cotton canopy on the frame at the back of a high clearance sprayer (Figure 3). A CSI Wireless GPS receiver (DGPS max) and the data acquisition unit were installed inside the sprayer's cab. The ultrasonic sensor was mounted 2.37 m above the ground surface. The sensor continuously scanned the cotton canopy, and the data acquisition system collected data from the sensor and GPS receiver as the vehicle travelled along the row at approximately 3.0 km/h. Two rows of cotton plants in each plot (the 6th and the 19th rows) were scanned using the ultrasonic system for plant height measurement on August 10, 2011. About 115 plant height measurements along with the spatial data were collected in each plot.

Figure 3. Ultrasonic plant height mapping system installed on a sprayer

Plant leaf-blade samples were collected from the scanned plots for analyzing the N content in leaf-blade tissues and determining relationships among the leaf N content, plant height, and yield. Due to wet field caused by rainfall, leaf-blade samples were collected in two days. Samples from plot numbers 101 to 212 were collected on August 16, 2011 and from plot numbers 301 to 412 on August 22, 2011. Ten uppermost fully expanded main-stem leaves were taken to make one leaf-blade sample. Three leaf-blade samples were randomly collected in each plot, resulting in 144 leaf-blade samples in total. Leaf-blade samples were oven-dried and analyzed for N content using the Kjeldahl method at Mississippi State University Extension Service Soil Testing Laboratory.

Non-irrigated plots were defoliated on September 8, 2011 and irrigated plots on September 23, 2011. Cotton was machine harvested with a spindle-type picker on October 11, 2011. Seed cotton from the 12 center-rows of each 24-row plot were transferred to a load cell-equipped boll buggy and weighed for yield determination. Each plant height measurement, combined with its spatial information, was processed for generating a plant height map. Average plant height of each plot was calculated by averaging all plant height measurements in the plot. The average of three leaf-blade N content values was calculated to represent plant N status in the plot.

Due to high soil residual N in the field, N application rate was not a good measure of N effect on yield. Therefore, in data analysis, leaf N was chosen to replace N treatment as a covariate with irrigation, leaf N, and irrigation*leaf N as fixed effects in the model. It was found that irrigation did not significantly affect the slope for leaf N ($F=1.33$, $p=0.2554$). So the fixed effect for irrigation*leaf N was eliminated from the model and the data were reanalyzed for the effect of leaf N on yield. The result showed that the effect of leaf N on yield was not significant ($F=0.08$, $p=0.7774$). An ANOVA was performed with SAS software using PROC MIXED procedure (SAS Institute Inc., Cary, NC) to evaluate the effect of irrigation on plant height, leaf N, and yield. In this analysis, irrigation treatment was a fixed effect; the block within irrigation treatment was a random effect and degrees of freedom calculations were based on Kenward/Roger option (Littell, Milliken, Stroup, Wolfinger, & Schabenberger, 2006).

Relationships between plant height and yield were determined. PROC MIXED in SAS was used to fit quadratic trends to explain differences in yield by plant height. Additionally, the mean, standard deviation, maximum, and minimum of plant height, leaf N content, and yield were calculated using the PROC MEANS procedure in SAS.

Plot number 212 was flooded several times due to accumulation of heavy rainfall and irrigation water caused by the water barrier built for preventing water from the irrigated block affecting non-irrigated plots. Excessive amounts of water in the plot resulted in undesirable growth patterns of plant biomass and caused shedding of cotton flowers and bolls, resulting in significant yield reduction. Data from this plot was therefore treated as an outlier and removed from the data set when data analysis was performed.

3. Results and Discussion

Due to experiments conducted in previous years, residual N in this field was high in general and varied greatly among plots, with a range of 21 to 194 kg/ha (Table 1). This situation affected leaf N levels, resulting in leaf N levels differing from those expected based on the N treatment design.

A summary of plant height, leaf N content, and yield of seed cotton is shown in Table 1 and Table 2. Plant height varied from 133.7 cm to 69.7 cm in non-irrigated treatments, and from 149.3 cm to 105.2 cm in the irrigated plots. Mean plant height in irrigated plots (M=125.0 cm, SD=13.4 cm) was greater than in the non-irrigated plots (M=95.1 cm, SD=11.1 cm). Average leaf N content values in non-irrigated and irrigated plots were 4.53% (SD=0.25%) and 4.97% (SD=0.50%), respectively. The lowest leaf N content was 3.73%, while the maximum was 5.74%. A critical value of cotton leaf N at early bloom in the Mid-South U.S. is 4% according to Bell et al. (1998), and cotton plants might be considered to be under N stress if leaf N concentrations are less than the critical value. Plants in this experimental field were not N deficient except in plot 405, in which the leaf N level was 3.73%. Due to the large amount of residual N in soil, cotton response to applied N rates was diminished. Mean yield in non-irrigated plots was 2975 kg/ha (SD=309 kg/ha) and 3399 kg/ha (SD=391 kg/ha) in irrigated plots. Overall, supplemental irrigation in this study increased cotton yield by 14.2%.

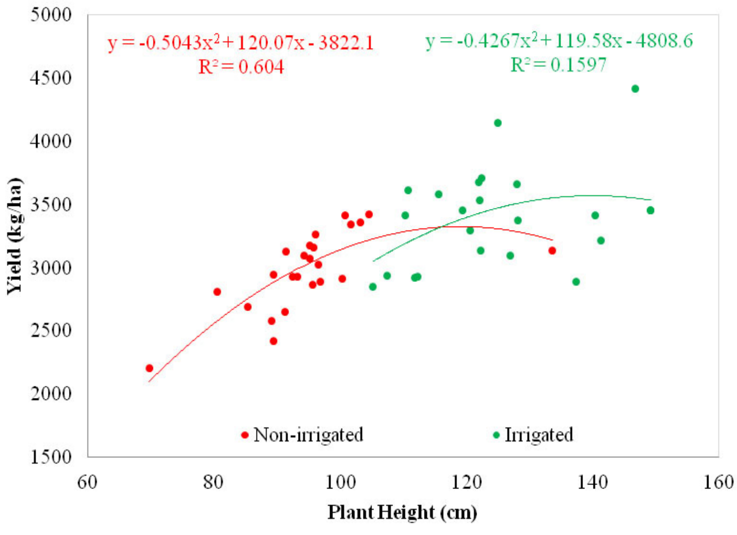

Figure 4. Relationship between plant height and yield in irrigated and non-irrigated plots

Table 1. Averages of plant height, leaf-blade N, seed cotton yield, residual N, and applied N in plots

Plot No.	Plant height (cm)	Leaf-blade N (%)	Yield (kg/ha)	Residual N (kg/ha)	Applied N (kg/ha)
101	100	4.63	2912	66	0
102	96	4.43	3021	122	135
103	103	4.47	3359	102	101
104	96	4.28	3262	87	39
105	89	4.25	2578	77	168
106	89	4.24	2943	87	67
107	110	4.81	3413	101	168
108	112	4.75	2923	168	101
109	121	4.88	3292	194	135
110	125	5.21	4144	183	0
111	140	5.74	3413	129	39
112	141	5.29	3212	39	67
201	97	4.51	2891	69	0
202	96	4.46	3158	63	67
203	94	4.49	3094	126	39
204	95	4.38	3074	78	135
205	91	4.28	2653	83	168
206	89	4.28	2418	102	101
207	127	4.48	3100	63	135
208	137	5.39	2891	30	168
209	149	4.49	3453	33	101
210	147	4.59	4417	27	0
211	149	4.91	3453	29	39
212	147	5.00	1967	34	67
301	111	4.67	3614	33	101
302	122	5.86	3533	34	168
303	122	5.41	3710	33	135
304	122	5.64	3132	21	67
305	122	4.85	3678	30	39
306	119	4.76	3453	52	0
307	92	4.39	2929	38	0
308	96	5.00	2869	21	101
309	105	4.82	3421	24	39
310	101	5.06	3415	24	168
311	91	4.68	3130	20	67
312	102	4.82	3339	126	135
401	112	4.55	2931	105	67
402	107	5.38	2939	165	168
403	105	5.08	2851	61	135
404	116	4.82	3582	63	101
405	128	3.73	3373	131	39
406	128	4.29	3662	90	0
407	85	4.60	2690	168	67
408	70	4.75	2208	177	0
409	95	4.50	3172	123	39
410	81	4.43	2811	140	168
411	93	4.08	2931	165	101
412	134	4.79	3132	119	135

Table 2. Variability in plant height, leaf-blade N, and yield within irrigated and non-irrigated plots. (Means with the same letter in each row are not significantly different at the 0.05 level)

	Irrigated Plots				Non-Irrigated Plots			
	Mean	Std Dev	Max	Min	Mean	Std Dev	Max	Min
Plant Height(cm)	125.0[a]	13.4	149.3	105.2	95.1[b]	11.1	133.7	69.7
Leaf-blade N (%)	4.94[a]	0.50	5.86	3.73	4.53[a]	0.25	5.06	4.08
Yield (kg/ha)	3399[a]	391	4417	2851	2975[b]	309	3421	2208

Plant height and yield for irrigated and non-irrigated plots, are plotted in Figure 4. Plant height showed a quadratic relationship with yield, and this relationship was stronger in the non-irrigated plots (R^2=0.60) than that in irrigated plots (R^2=0.16). However, the trends of those two models did not significantly differ (F=1.11, p=0.3402). It was noted that the plant height in plot 412 was much greater than other plots in the non-irrigated blocks, possibly due to its soil composition and location within the field. This plot was in the northwest corner of the field (Figure 2), and field slope allowed this plot to receive more runoff from rainfall than other non-irrigated plots. Good soil texture with sufficient water created a favorable environment for plants in this plot, allowing them to grow taller than the others. Plant height in non-irrigated plots showed a strong linear correlation (R^2=0.66) with yield if plot 412 was excluded.

A plant height map of the field is shown in Figure 5, and illustrates that plants in irrigated areas were taller than in the non-irrigated areas. Comparing the plant height map with the soil EC map, a trend was observed in which locations with higher EC had lower plant heights. This suggests that soil EC might be added as another layer of information when using plant height in development of site-specific crop management strategies in cotton (Huang, Sui, Thomson, & Fisher, 2012).

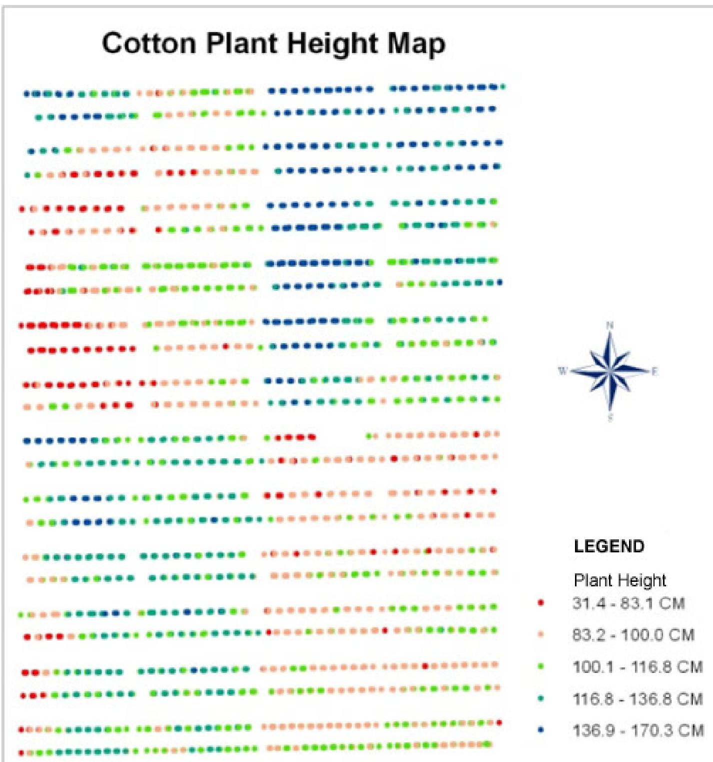

Figure 5. Cotton plant height map created using data collected by the ultrasonic plant height mapping system

Irrigation had a significant effect on plant height, leaf N content, and yield. ANOVA revealed that plant height differed significantly as a function of irrigation (F=17.00, p=0.0549). The ANOVA also indicated the yield of irrigated cotton was significantly different from that of the non-irrigated (F=17.02, p=0.0002). Irrigated plants had a higher leaf N concentration than the non-irrigated, suggesting that the plants' ability to use N from soil could be enhanced by higher soil moisture content. However, the ANOVA test showed that leaf N differences between irrigated and non-irrigated plots were not significant (F=9.00, p=0.0922).

Since the plants were not under N stress, and leaf N had little variation across the plots, linear regression analysis showed that the leaf N content had a weak correlation with both plant height and yield in this study. Once cotton plants received sufficient N, excess application of N would not improve cotton yield, and it could possibly create a negative impact on yield, production cost, and environment.

The plant height mapping system used in this study was easy to install and operate. System installation took a person about one hour. Tools required for the installation were a handheld drill, wrench, and screwdriver. During the field operation, no mechanical or electrical problems occurred. In terms of its operation software, the system also performed well in collecting, organizing, and storing data. Twenty four data files were successfully generated, and all data collected were effective.

4 Conclusions

A plant height measurement system was used to map cotton plant height across an experimental field in the Mississippi Delta. Plant height was measured using an ultrasonic sensor to scan the plant canopy while spatial information was collected by the system from a GPS receiver. Average cotton plant height of individual plots in the field was determined and a plant height map of the field was created. Plant height at first bloom stage had a fairly close quadratic relationship with seed cotton yield. Irrigation had a significant effect on plant height and yield. Compared to the non-irrigated, irrigated cotton plants grew taller, had higher leaf N concentration, and yielded 14.2% more seed cotton. The variation of plant height could be easily identified on the map and compared favorably to visible field conditions. During plant height data collection, the mapping system performed well. On-the-go measurement and mapping of plant height could be a useful tool in diagnosis of plant growth conditions and decision making for site-specific crop management in cotton production.

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