EVALUATION OF COTTON HEIGHT MEASUREMENT TECHNIQUES

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Abstract

Site-specific crop management (SSCM) is a farming method which takes advantage of field variability to optimize the management of a site. Application of SSCM techniques requires knowledge of the spatial variability present in the field and equipment which is capable of applying production inputs in such a way as to address those spatially variable needs. A cotton height sensor was developed and evaluated to provide knowledge of spatially variable cotton heights in an actively growing field. A GPS-controlled direct injection sprayer was assembled from commercially available components and tested by applying growth regulatory chemicals to a cotton crop.

A cotton height sensor was developed and evaluated to determine its ability to measure and record cotton heights across a field. Geo-referenced position was recorded with the height sensor output to provide a means by which a map of the cotton height across the field could be made. The cotton height sensor utilized two separate sensing methods for cotton height determination. An infrared light curtain was used to obtain height values within ±33 mm (1.3 in.) of hand measured values. A bank of limit switches with arms contacting the plants was used on the same implement, but the resolution was only ±46 mm (1.8 in.). Both methods were evaluated for damage to the growing crop, and damage was within 10% of what a normal cultivation pass might cause. The prototype sensor was found to be capable of farm scale use on a daily basis.

Introduction

Cotton (*Gossypium hirsutum*) plant management is a process which all cotton producers must concern themselves with each year. One aspect of plant management is control of the plant's growth during the season. Mepiquat chloride (Pix®) is a plant growth regulator commonly used in cotton production to limit the vegetative growth of the cotton plant. Required application rates for this chemical are related to the amount of biomass present in the cotton plant. Cotton height is an estimator of the amount of biomass present and is therefore one of the crop variables used to determine the amount of plant growth regulation required by the cotton plant (Landivar, 1995). Other variables include number of nodes and plant population. A method by which cotton height can be assessed as it varies across a field is desirable as an aid in determining the correct plant growth regulation rates for that field. An accurate cotton plant height map can be used to create a variable rate application map for the plant growth regulator. The cotton height information can also be used to provide more accurate estimations of production potential throughout the growing season. Factors such as water stress, insect pressure, and specific soil influences across a field might also be better determined on a spatial basis with accurate cotton height information.

Reprinted from the *Proceedings of the Beltwide Cotton Conference*
Volume 1:547-554 (1999)
National Cotton Council, Memphis TN

Objectives

The objectives of this research were to develop a cotton height sensor for field use and to evaluate that cotton height sensor under field conditions. These research objectives were undertaken to determine if a method of field scale cotton height determination could be created. Development of the cotton height sensor required investigation into numerous sensing methods through both literature and testing. Evaluation of the cotton height sensor required development of a prototype for field use. GPS positioning information was also linked to the cotton height information so that a GIS could be used to take full advantage of the information on a spatial basis.

Materials and Methods

Operating specifications for the height sensing systems were based on the desire to use the height information for mepiquat chloride rate determinations. Potential sensor designs were constructed and field tested. The height estimates generated by the sensor systems were compared to manual height estimates for development of calibration equations and evaluation of the sensor accuracy. Following the determination of the optimum calibration technique, the impact of the sensor errors on mepiquat chloride application rates was examined. Each of these steps in the research process are discussed in the following sections.

Design Specifications

The height sensor was to be used on a growing cotton crop throughout the growing season, so three basic design specifications had to be met. The first specification was that the system must be non-destructive to the cotton plants. The damage to the growing cotton crop was to be no more than 10% greater than the damage incurred from a routine cultivation pass. The second specification was that the system be dependable and reliable in agricultural environments, which included dust, sunlight, heat, wind, and humidity. The third design specification was to measure cotton height within ±25 mm (1 in.) over a range of heights from 0.25 to 1.0 m (10 to 40 in.). This height range was selected to cover the cotton plant sizes expected in dryland production for the Texas Coastal Bend region.

Sensing Alternatives

The non-contacting sensing options were examined against the environment in which they would operate. Reflectance sensors were eliminated as choices due to their inability to resolve small changes in plant height. Due to its ability to distinguish small changes in plant heights, a bank of photoelectric thru-beam sensors was chosen as one sensor type. The sensor was assembled from commercially available components (Banner BMEL3016A emitter bar, BMRL3016A receiver bar, and QDC-525C controller). This system (referred to as MAC) had 40 beams spaced over a 0.76 m (30 in.) vertical scanning range. Output from the controller was via a 9-pin RS-232

A second sensor based on plant contact was constructed. Since the system had to be non-destructive, the contacting arms of the sensors had to swing with ease away from the cotton plants when contacting them and return to a neutral position when no plants were present. A series of limit switches was chosen to evaluate this concept. The sensors were placed beside the row of cotton with arms projecting across and perpendicular to the row. Plant presence would cause the switch arm(s) to swing back due to travel of the height sensor. A bank of 12 switches was constructed at an interval of ±25 mm (1 in.).

Cotton Height Sensor Design

The initial prototype design of the cotton height sensor is shown in Figure 1. The MAC emitter and receiver bars were placed on separate slides to provide consistent height above the ground from which measurements were referenced. Both bars were bolted to a common toolbar to maintain their alignment. The toolbar was connected by a parallel linkage to another toolbar which connected to the three point hitch on a tractor. The slide with the MAC receiver was extended to accommodate the bank of switches behind it (Fig. 1). The size of the switch bodies with sensing arms attached prohibited their placement in one vertical column with 25 mm (1 in.) spacing between them. Therefore, four separate columns were used to mount the switches. The switches were mounted in a staggered fashion so as to provide the desired 25 mm spacing between consecutive switches. A drawback of this offset design for the switches was the possibility for cotton heights to influence switches higher up at the back of the sensor than at the front. For example, a tall plant could still have the back switch held in an activated position while a lower switch already past that plant has returned to its neutral position. However, the prototype would still be suitable for conceptual proof of design.

Data Acquisition

Data acquisition for the cotton height sensor was done with an on-board computer in the tractor cab. The MAC was linked directly to a RS-232 serial port in the computer. The limit switches, henceforth referred to as simply switches, were connected to the computer through a digital input/output port. An Omnistar 7000 receiver was used to receive the differential global positioning system signals. The receiver was mounted on top of the tractor cab, and it was connected to the computer through a RS-232 serial port. The components described were used to record the height sensor output. The computer ran a C++ program to read the MAC and switch outputs while recording the DGPS position. Post processing of the information was required to separate the switch and MAC data for analysis. Height data was recorded at approximately nine hertz.

Hand Measurements of Cotton Height

The hand measurements of cotton height were the basis for determining the accuracy of the cotton height sensor. Two separate hand measurements, plant height and canopy height, were made in a series of test plots. Cotton plant height was defined as the height of an individual cotton plant measured from the ground at the base of the stalk to the uppermost node of the main stalk. Cotton canopy height was defined as the apparent height of a meter-long section of row. The canopy height measurements generally produced values associated with the height of the uppermost leaves of the majority of the plants in the section under consideration. They did not typically represent the cotton plant heights to the uppermost nodes. In this measurement, smaller plants were generally ignored while the larger plants in the one meter row section dominated the canopy.

Hand Sampled Data Collection

All reported data was collected in a 40.5 ha (100 ac) cotton field in 1998 in the Coastal Bend near Kingsville, Texas, on the King Ranch. The climate is semiarid, and 1998 was a particularly dry year. The cotton variety on which the height sensor was tested was DP-5690-RR, and the crop was not irrigated. The emergence date for the cotton tested was March 20, 1998.

Data was collected on three separate trips to the cotton field. The first data set was collected on May 20. The date of the second data collection effort was June 10-11, and the final data was collected on July 16. Plots were laid out for the May trip by placing staked 0.6 X 1.2 m presswood boards in the cotton row to be measured. The boards were intended to be clearly visible in the height sensor data, and they were to indicate the beginning and end of the test areas. Two such boards were placed side-by-side to mark the ends of each plot during June and July data collection to ensure clear demarcation for the height sensor data analysis. Plant height and canopy height measurements were made within each plot after the boards were in place and before the height sensor was used on the plots. Measurements for the May data were made to the nearest 2.54 cm, while measurements for the June and July data were made to the nearest centimeter. The distance from the North end of each plot was recorded with each plant height measurement for the June and July data sets. The length of the plots varied with each trip as more information was learned from the height sensor data analysis. Eleven plots of 6.1 m length were established for data collection in May. For the June trip, ten plots of 13 m length were used. The July data was collected in two plots, each having a length of 30.5 m.

The staked boards were used to mark the plots on each trip to aid in data analysis. The boards at each end of the plots served to mark the data sets by indicating a constant height taller than any of the cotton plants in the field. These marked areas in the data set later served to denote the beginning and ending of each plot. Occasionally, though, the boards did not clearly appear in the sensor data. As a result, some data sets could not be directly compared to the hand measured height data. Table 1 shows a summary of the data which was used in cotton height sensor evaluation. The MAC and switch measurements denote the two methods of data collection used on the height sensor, and they are discussed in later sections of this manuscript. The sets shown in Table 1 are simply references used later in this manuscript to the specific groupings of different measurements. The set letters found on multiple groupings indicate paired comparisons between the groups. Pairings were made between groupings based on the distances associated with each measurement, and those distances had to be within ±76 mm (3 in.) before the values would be paired. Also, the references used in this manuscript may refer only to the measurement being discussed instead of all groupings with the same set letter. For instance, in a set which includes both plant and canopy height measurements, only plant height measurements would be used for analysis of plant height relationships.

Field Operation

The first data was collected with the cotton height sensor as described on May 20, 1998, on the King Ranch near Kingsville, Texas. Two other data collection times at the same location were June 10-11 and July 15, 1998. Tests of the initial prototype were conducted at different times of the day, at different speeds, and repeated on the same plots for confirmation of repeatability of the measurements. Plots were laid out in the field as previously described with boards at each end. Testing at different times of the day was done to determine what, if any, influence different sun angles might have on the MAC output. Increased wilting throughout the day was also considered when testing at different times of the day.

Data Analysis

Analysis of the data was done with a spreadsheet computer program and SAS® software. The MAC and switch data were first separated for individual analysis. DGPS readings were maintained in their original positions within each data set. The format of the data files was such that a 1 or 0 was recorded for each sensor on the height sensor assembly. A 1 was representative of a blocked or tripped sensor (indicating plant presence), while a 0 represented no blockage or activation of the switch. The raw MAC data, as shown in Table 2, consisted of a series of 1's and 0's with no apparent pattern. Naturally occurring voids in the cotton canopy allowed lower beams to be transmitted which caused the irregular pattern. Another possible cause of the irregular pattern is the fact that the MAC sensors were scanned sequentially, which resulted in some forward travel distance between the top sensor and the bottom sensor readings for each scan. The solid bank of zeros on the left side of the data set indicated that no cotton plants were as tall as the sensors in that height range. The switch data, as shown in Table 3, was more consistent. The blocked and unblocked areas were much more clearly defined and without the frequent gaps associated with the MAC data.

After exploring several different methods for data analysis with linear regression, the following methods were chosen as most suitable. Plant height data, as collected by hand in the field, was averaged with a 31-measurement moving average. Canopy height measurements were averaged with a 9-m moving average. MAC and switch height estimates were averaged over an approximate distance of 5 m ($\approx$16 ft) with a 31-reading moving average. Prior to averaging, zero readings were dropped from the MAC data set since they did not represent plant or canopy heights. These zero readings represented gaps in the planted row. No zero readings were found in the switch data sets. In order to compare sensor height estimates to the canopy height measurements, the sensor estimates corresponding to each canopy measurement were averaged. This averaging provided a single height estimate that could be directly compared to the canopy measurement. The 9-m moving average was then performed on both sensor estimates and canopy measurements. A second method of comparing height sensor output to canopy heights was also used. This second method paired the 9-m moving average of canopy heights to the appropriate value, as determined by distance, from the 5 m moving average of height sensor output.

Mepiquat Chloride Rate Determination

The final method of cotton height sensor evaluation involved a comparison between mepiquat chloride (MC) rates for hand measured plant heights versus height sensor output. One of the factors in MC rate prediction is plant height , so holding the other variables constant while varying the plant height allowed a comparison to be made between the rates. This comparison was made to determine how the error in the height sensor output would impact the application rate of the MC, which is a possible application of the height sensor output. A paired T-test was used to compare the rates.

Results and Discussion

Non-Contacting Sensor Plant and Canopy Height Estimates

The relationships between both plant height and canopy height to MAC output were determined through multi variate linear regression with SAS® using the *proc reg* command on set A data from Table 1. An equation was developed for plant height with days since emergence (time) and a 5 m moving average of MAC top blocked sensor heights as the two independent variables. The plant height value to which these were related was a 31-measurement moving average. The equation which related plant height (cm) to MAC height sensor output (cm) is shown in equation 1.

$$\text{Plant Height} = 0.92*\text{MAC} + 0.11*\text{time} - 2.2 \quad (1)$$

The R^2 value for this regression was 0.95 (Fig. 3). Note that Figure 3 shows only a representative sample of the verification data from plot 4 collected at midday on June 11, and values at both ends of the shown graph reflect influence from the full data set through the moving average scheme used in data analysis. An alpha value of 0.05 was used for all analyses. 2336 readings were used in the development of the regression equation. The 95% prediction interval for cotton plant height estimation was ±33 mm (1.3 in.). The equation developed for canopy height had the same time variable, but the MAC variable was a 9-m moving average of the canopy height estimations from the MAC height sensor output. The equation which related MAC output (cm) to canopy height (cm) is shown in equation 2.

$$\text{Canopy Height} = 0.79*\text{MAC} + 0.15*\text{time} + 4.4 \quad (2)$$

The R^2 value for this regression was 0.94 (Fig. 4). The values were determined from a data set consisting of 275 points. The 95% prediction interval for canopy heights was ±30 mm (1.2 in.). All parameter estimates given for both plant height and canopy height were statistically significant at the $\alpha = 0.05$ level.

Verification of these statistical values was attempted by applying the regression equation to data collected at different times (set B, Table 1). Set B consisted of 1895 readings for the plant height relationship. Figure 5 shows a cumulative distribution of the errors in plant height prediction compared to measured values. Due to a programming error during the May data collection trip, repeated measurements were not made on those plots. Note that Figure 3 shows only a representative sample of the verification data from plot 4 collected at midday on June 11, and values at both ends of the shown graph reflect influence from the full data set through the moving average scheme used in data analysis. As indicated by the cumulative distribution graph (Fig. 5), only 88% of the readings were within the ±33 mm (1.3 in.) range of measured plant heights. This lack of prediction interval verification, though, could be strongly influenced by the one centimeter precision of the hand measurements used for verification.

Verification was attempted for the canopy height relationship described on data collected at different times during June and July (set B, Table 1). 198 readings were contained in set B for the verification. Figure 6 shows a cumulative distribution of the error values between actual and predicted canopy heights. Only 68% of the errors fell within the bounds of the prediction interval of ±30 mm (1.2 in.). Lack of prediction interval verification by such a large percentage seemed to indicate a possible repeatability problem with the MAC sensor. The subjective nature of the canopy height measurements may also have impacted the lack of prediction interval verification. The cumulative error distribution (Fig. 6) demonstrates an approximate 2 cm offset which could be the result of an inappropriate constant value in the canopy height regression equation. The equation was applied to the verification data without any modification to correct this apparent offset. Shifting the prediction interval so that it is centered about -2 cm, however, increases the percentage of data inclusion to approximately 88%.

Contacting Sensor Plant and Canopy Height Estimates

The relationships between both plant height and canopy height to switch output of the cotton height sensor were determined through multi variate regression analysis. An alpha value of 0.05 was used for all analyses. The time variable was the same as mentioned with the MAC relationship. The switch variable for both plant height and canopy height equations was a 5 m moving average of switch values centered at the distance corresponding to the middle reading of the moving average. Data used for equation development is shown in Table 1, set C. Due to a data acquisition programming error, no data was included from the May trip for switch analysis. The equation which related plant height (cm) to switch output (cm) is shown in equation 3.

$$\text{Plant Height} = 0.88*\text{Switch} + 0.035*\text{time} - 1.6 \quad (3)$$

R^2 for this regression relationship was 0.64 (Fig. 7). 1232 readings were used in the development of this regression equation. The 95% prediction interval for cotton plant heights based on switch output was ±46 mm (1.8 in.). The intercept term was the only parameter which was not significant, and it was not significantly different than zero at $\alpha = 0.05$. The equation which related canopy height (cm) to switch output (cm) is shown in equation 4.

$$\text{Canopy Height} = 0.68*\text{Switch} + 0.11*\text{time} + 6.2 \quad (4)$$

R^2 for this regression relationship was 0.63 (Fig. 8). Note that Figures 7 and 8 show only plot 4 from the June 11 midday data collection used for verification of the reported prediction intervals. 148 readings were used in the development of this regression equation. The 95% prediction interval for cotton canopy heights based on switch output was ±43 mm (1.7 in.). The apparent data shift of approximately two meters in Figure 7 seemed to indicate that an error in data analysis had occurred, but Figure 8 did not show the same offset. No errors were made in the data analysis to cause this apparent shift.

Verification of the reported values was conducted on data denoted by set D, Table 1. 1502 readings were contained in set D for the plant height relationship, and 184 readings were in the canopy height verification data. Figure 9 shows a cumulative distribution of the errors between the measured plant height values and the predicted values from the switch output. 95% of the errors were within the predicted range of ±46 mm (1.8 in.). Figure 10 shows a cumulative distribution of the errors between the measured canopy height values and the predicted values. 96% of the errors were within the predicted range of ±43 mm (1.7 in.).

Effect of Travel Speed

The cotton height sensor was evaluated at two speeds in addition to the 1.6 m/s speed used for primary evaluation (0.8 m/s and 1.9 m/s). Plant height relationships were tested at these speeds. Evaluation suggested that the height sensor, using the same multi variate linear regression equations developed from 1.6 m/s data, could not predict plant height with the same prediction bounds and confidence at different speeds. Data used for the travel speed analysis is outlined in Table 1. Set E data was used for evaluating the MAC data at 0.8 m/s, while set F data was used for 1.9 m/s MAC evaluation. The switch data used for 0.8 m/s evaluation is denoted by set G, and the 1.9 m/s switch evaluation was conducted with data denoted by set H. By altering the number of values used in the moving averages for both MAC and switch data, the same 5 m linear distances were compared to the 31-measurement moving average of plant heights. At 0.8 m/s, 55 readings were used for the MAC and switch moving averages. The MAC 95% prediction interval was ±40 mm (1.6 in.), and the switch 95% prediction interval was ±50 mm (2 in.). At 1.9 m/s, 23 readings were used in the moving averages to represent the 5 m linear distance. The MAC 95% prediction interval was ±40 mm (1.6 in.), while the same interval for the switches was ±100 mm (4 in.). The conclusion, therefore, was that the relationship between height sensor output and plant heights is dependent on the speed of data collection. More targeted research would be required to determine the height sensor's ability to predict cotton plant heights at varying field speeds.

Repeatability and Time of Day Analysis

The repeatability of the cotton height sensor output was analyzed by performing simple statistical analysis on multiple passes over the same plots. The data from each pass was grouped by plot number in which it was collected and pass number. The canopy height estimations were averages of all height sensor output for a given canopy height measurement distance without any regression. Plots 3, 4, 6, and 7 from the afternoon data collection on June 10 were examined in this fashion. A Duncan multiple range test was conducted with SAS® to determine if the means of each pass were significantly different within each plot. For the MAC output with $\alpha=0.05$, the passes were not significantly different within any of the four plots. The means of plots 3 and 4 were not statistically different from one another. Plots 6 and 7 were not statistically different from one another, either. Switch output was analyzed in the same manner, but the data included only 6 passes from plot 3, 5 passes from plots 4 and 6, and 7 passes from plot 7. The reason for the difference in data amounts was incomplete switch activation by the boards in the field to identify the plots in the data set. The results verified that the mean of the multiple passes within each plot were not significantly different from one another for the switch output. The means of all plots from the switch analysis were statistically different from one another. The conclusion from these repeatability analyses was that both the MAC and switch output were consistent and repeatable. Their accuracy was not considered in these analyses.

Data was collected with the cotton height sensor data at different times of the day to determine the influences of different sun angles and/or degree of wilting on the MAC output. Switch data was not analyzed in this fashion because the switches are activated by contact with the plant, which would not change significantly throughout the course of the day. Plots 1, 2, 5, and 8-10 from the June trip were analyzed for repeatability during different times of the day. The times of day examined were morning, midday, and afternoon. Height sensor output was grouped into canopy height estimations and arranged by plot number and time of data collection as with the repeatability analyses. The results of the Duncan multiple range test verified that the means of the canopy height estimations from each time of day within each plot were not significantly different from one another with $\alpha=0.05$. The test also indicated that three statistically different means were found among the data analyzed. The means were grouped such that plots 1, 2, and 8 were together, plots 5 and 10 were together, and plot 9 was statistically different from all plots. The accuracy of the MAC output was therefore not dependent of the time of data collection.

Mepiquat Chloride Rate Prediction

A paired T-test was performed on the mepiquat chloride rates based on hand measured plant heights and MAC height estimates. The plant height values were 31-measurement moving averages of measured values, and the MAC heights were from the 5 m moving average with multi variate regression. The data set used for this analysis was the same as that used for verification of the MAC plant and canopy height relationship (set B, Table 1). The mean of the differences in rates (measured - MAC) was -4.6 ml/ha (-0.064 oz/ac). The standard deviation was 17.5 ml/ha (0.24 oz/ac). The minimum difference was -80 ml/ha (-1.1 oz/ac), and the maximum was 51 ml/ha (0.7 oz/ac). Though the paired T-test revealed that the two rates were significantly different from one another, the mean difference was less than 7.3 ml/ha (0.1 oz/ac) in magnitude. Since 1895 readings were included in the analysis, a small difference would become statistically significant. In practice, a difference in application rates of less than 7.3 ml/ha would not be significant to a producer, and application equipment might not even be able to apply differences of less than 7.3 ml/ha (0.1 oz/ac).

Summary and Conclusions

Two prototype cotton height sensors were field tested and found to predict cotton plant heights within ±33 mm (1.3 in.) and ±46 mm (1.8 in.) for the non-contacting and contacting systems respectively. The predicted cotton plant heights are representative of a moving average of approximately 5 m of row length. The intrinsic averaging in the cotton height sensor predictions provides better representation of the general trends in the cotton height variability as opposed to specific detail about small portions of the row being measured. Differentially corrected global positioning system position was recorded with the prototype sensor height predictions to allow the height information to be mapped with GIS software.

The prototype cotton height sensor met two of the three intended design specifications under which it was conceptualized. It was a non-destructive tool to measure cotton plant heights which was reliable enough for farm scale use, but it couldn't predict cotton heights within ±25 mm. The MAC, which had the smallest prediction interval and was the best method of plant height detection, was only able to predict 88% of the plant heights within ±33 mm, but the project was still a success in that the concept of cotton plant height detection was proven. The switches did not approach the desired resolution requirements, but design modifications could improve their ability to resolve smaller changes in plant height.

The cotton height sensor was designed as a tool for improving cotton plant management. One way in which it could accomplish that task is by providing a basis from which variable rate chemical application maps could be created. Evaluation of the cotton height sensor's ability to create variable rate mepiquat chloride (MC) application maps demonstrated its ability to accurately predict rates similar to what actual plant heights would require. The MAC height estimates were used to predict MC rates for set B (Table 1) data. The mean of predicted rates was within 7.3 ml/ha (0.1 oz/ac) of the mean of the rates from plant height measurements. The MAC estimates could therefore be used to provide variable application rates which are within the adjustment increments of 7.3 ml/ha (0.1 oz/ac) commonly found on application equipment. For greater detail about this research, see Stewart (1998).

Bibliography

Landivar, J. A. 1995. The effect of estimated plant concentration of Pix on leaf area expansion and main stem elongation rate. Proceedings Beltwide Cotton Conference. 1081-1085.

Stewart, J. H. 1998. Cotton Height Measurement and Variable Rate Chemical Control. Master's thesis. Texas A&M University.

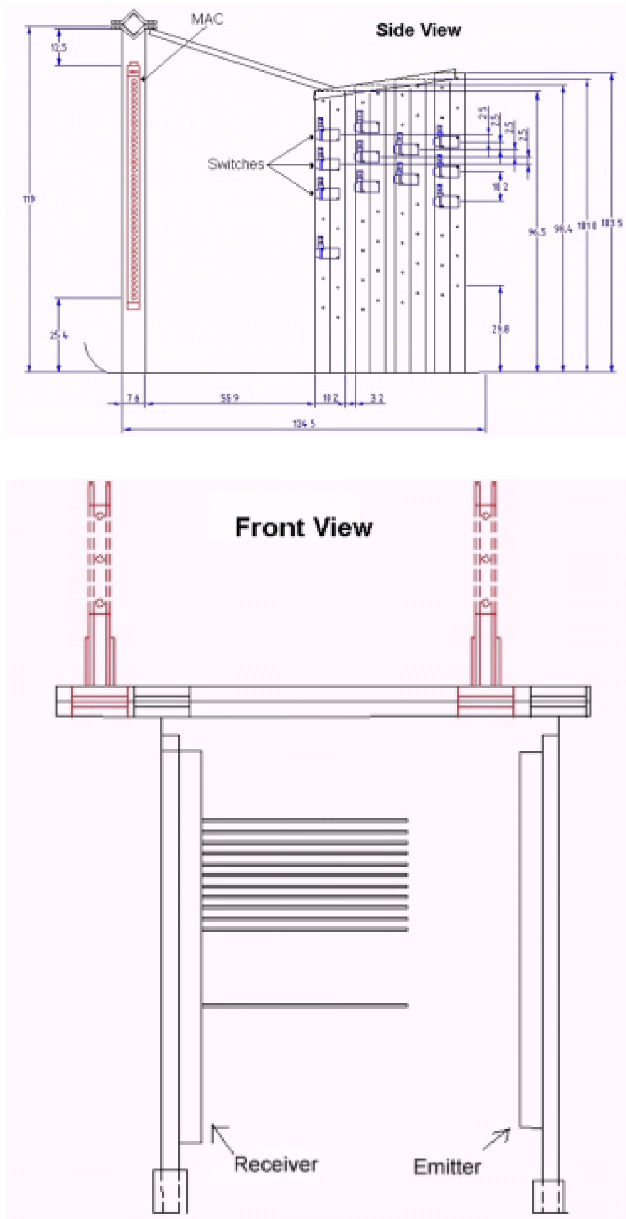

Figure 1. Side and front views of cotton height sensor. Side view shows infrared sensors (MAC) on left side and switch bank on the right. Dimensions shown in centimeters.

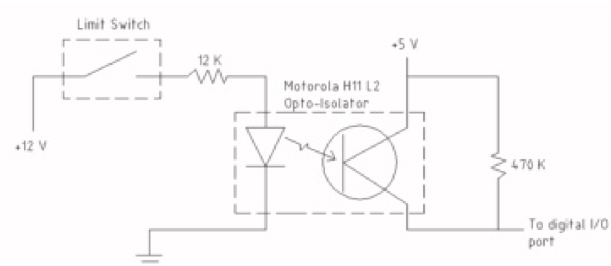

Figure 2. Schematic diagram of circuit used for logging of switch data on cotton height sensor.

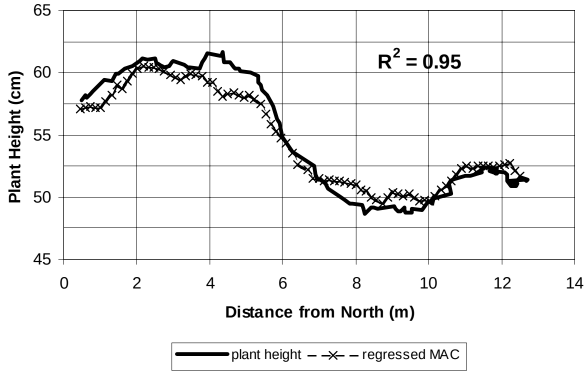

Figure 3. Graph of 31-reading moving average of plant height values and predicted heights from multi variate regression of MAC data. Values at beginning and end of shown lines reflect influence of full data set instead of just plot 4 from June 11, 1998, midday.

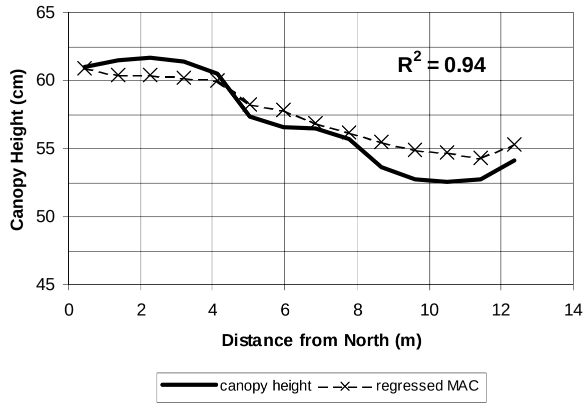

Figure 4. Graph of 9-reading moving average of canopy height values and predicted heights from multi variate regression of MAC data. Values at beginning and end of shown lines reflect influence of full data set instead of just plot 4 from June 11, 1998, midday.

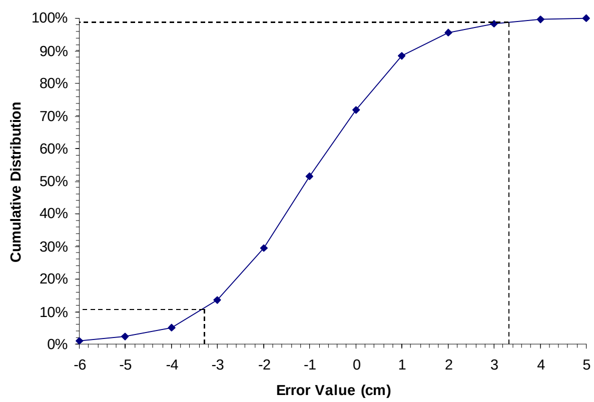

Figure 5. Cumulative distribution of errors in predicted plant height from MAC output for 10 plots from midday June 11 and 3 plots from afternoon July 16, 1998.

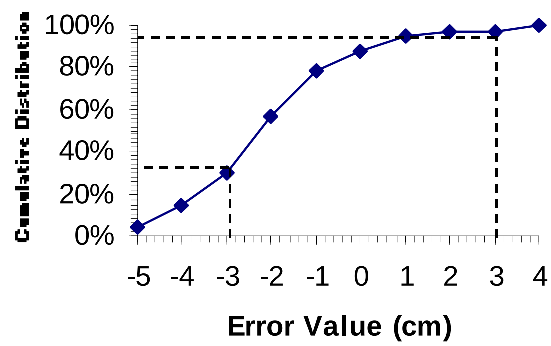

Figure 6. Cumulative distribution of errors in predicted canopy height from MAC output for 10 plots from midday June 11 and 3 plots from afternoon July 16, 1998.

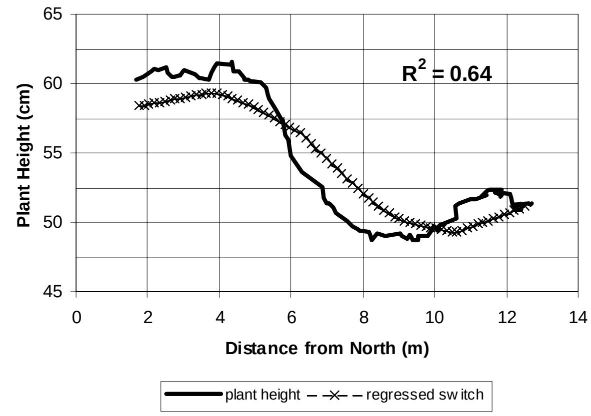

Figure 7. Graph of 31-reading moving average of plant height values and predicted heights from multi variate regression of switch data. Values at beginning and end of shown lines reflect influence of full data set instead of only plot 4 from midday June 11, 1998.

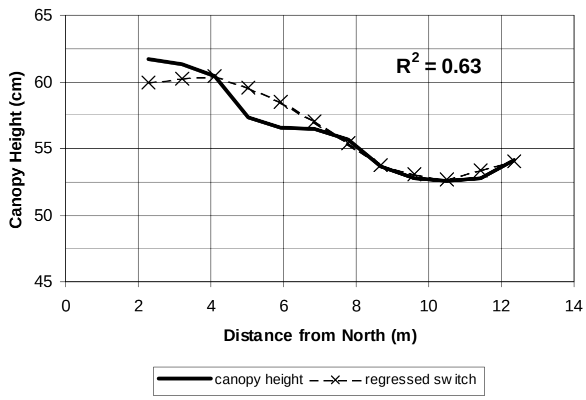

Figure 8. Graph of 9-reading moving average of canopy height values and predicted heights from multi variate regression of switch data. Values at beginning and end of shown lines reflect influence of full data set instead of only plot 4 from midday June 11, 1998.

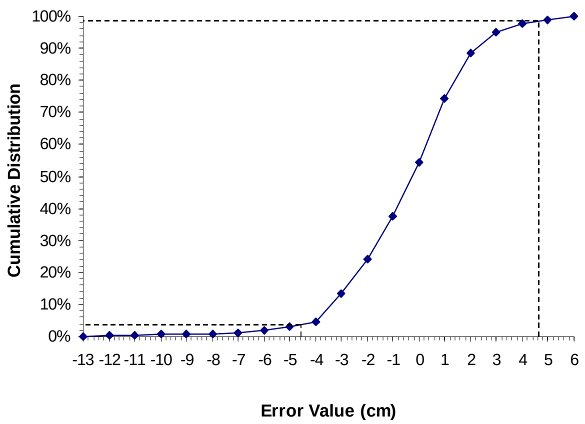

Figure 9. Cumulative distribution of errors in predicted plant height from switch output for 10 plots from midday June 11 and 1 plot from afternoon July 16, 1998.

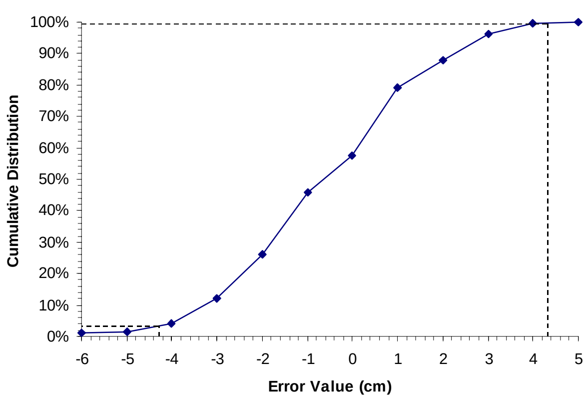

Figure 10. Cumulative distribution of errors in predicted canopy height from switch output for 10 plots from midday June 11 and 1 plot from afternoon July 16, 1998.

Table 1. Data collection summary

Measurement	Date (1998)	Plots	Speed (m/s)	Time of Day	Set
Plant Height	5/20	1 - 11	N/A	N/A	A, F
Canopy Height	5/20	1 - 11	N/A	N/A	A
MAC	5/20	1 - 11	1.6	Afternoon	A
MAC	5/20	1 - 11	1.6	Afternoon	F
Plant Height	6/10	1 - 10	N/A	N/A	A, B, C, D, E, F, G, H, I, J
Canopy Height	6/10	1 - 10	N/A	N/A	A, B, C, D, I, L
MAC	6/10	1 - 10	1.6	Afternoon	A, K
MAC	6/10	3, 4, 6, 7	0.8	Afternoon	E
MAC	6/10	3, 4, 6, 7	1.9	Afternoon	F
Switch	6/10	1 - 10	1.6	Afternoon	C
Switch	6/10	3, 7	0.8	Afternoon	G
Switch	6/10	3, 4, 6	1.9	Afternoon	H
MAC	6/11	1 -10	1.6	Midday	B
Switch	6/11	1 - 10	1.6	Midday	D
MAC	6/11	1-2, 5, 8-10	1.6	Morning	M
Plant Height	7/16	1 - 2	N/A	N/A	A, B, C, D
Canopy Height	7/16	1 - 2	N/A	N/A	A, B, C, D
MAC	7/16	1a, 2a*	1.6	Afternoon	A
MAC	7/16	1b, 2b, 2c	1.6	Afternoon	B
Switch	7/16	1a, 2a	1.6	Afternoon	C
Switch	7/16	2b	1.6	Afternoon	D

*Note: Letters following plot numbers denote multiple passes on the same plot.

Table 2. Raw MAC data with uppermost sensor values removed for representation

MAC	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 0 0 0 1 0 0 1 1 1 0 1 1	0
MAC	0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0 0 0 1 0 0 0 0 1 0 0 0 0 0	1
MAC	0 0 0 0 0 0 0 0 0 0 1 1 1 0 1 1 1 1 1 1 1 0 0 0 0 0 1 1 1 1 0 0 1 0 0	0
MAC	0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 1 1 0 1 1 1 1 1 0 1 1 1 1 0 1 1 0 0	0
MAC	0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 1 1 1 0 0 0 0 0 0 0 0 0 1 1 1 0 0 1 1	0
MAC	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 1 1 1 0 1 1 1 1 1 1 1	0
MAC	0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 1 1 0 0 0 0 1	1
MAC	0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 1 1 1 1 1	0
MAC	0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 0 1 0 0 0 0 1 1 1 0 0 0 0 1 0 1 1 1 1	0
MAC	0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0 1 1 1 1 1	1
MAC	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0 0 0 0 0 0 0 0 1 0 0 1 1 1 1	1

TOP BOTTOM

Note: Data collected such that top row of table is first scan, second row is second scan, etc.

Table 3. Raw switch data showing all output from height sensor

Switch	0	0	0	0	0	1	1	1	1	1	1	1
Switch	0	0	0	0	0	1	1	1	1	1	1	1
Switch	0	0	0	0	0	1	1	1	1	1	1	1
Switch	0	0	0	0	0	1	1	1	1	1	1	1
Switch	0	0	0	0	0	1	1	1	1	1	1	1
Switch	0	0	0	0	0	1	1	1	1	1	1	1
Switch	0	0	0	0	0	1	1	1	1	1	1	1
Switch	0	0	0	0	0	1	1	1	1	1	1	1
Switch	0	0	0	0	0	1	1	1	1	1	1	1
Switch	0	0	0	0	0	0	1	1	1	1	1	1
Switch	0	0	0	0	0	0	1	1	1	1	1	1

TOP BOTTOM

Note: Data collected such that top row of table is first scan, second row is second scan, etc.