IRRIGATION EFFICIENCY STUDY BASED ON DSSAT CSM-CROPGRO COTTON MODEL CALIBRATED WITH IN-SEASON DATA FROM THE TEXAS HIGH PLAINS

A Thesis

by

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ABSTRACT

The Texas High Plains form a unique region that has been a vital part of U.S. grain and fiber production for many decades. Areas in the Texas High Plains are experiencing the effects of conflicting interests in a diminishing water source, the Ogallala Aquifer. Proposals have been made to limit the quantity of water withdrawn from the aquifer for irrigation purposes, leading to increased interest in the adoption of efficient irrigation strategies. Decision Support System for Agrotechnology Transfer (DSSAT) is a modeling software that uses meteorological, soil, and field experimental data to predict crop growth, development, and yield, and it is very useful for evaluating the efficiency of crop and irrigation management strategies. This study details the calibration and verification of a DSSAT experiment based on an unpublished 2008 field study performed by the United States Department of Agriculture Agricultural Research Service (USDA-ARS) and the use of the calibrated model for determining best irrigation strategy in terms of crop yield and water use efficiency. The field study was conducted to compare the effects of different irrigation strategies on cotton yield. Due to the wealth of in-season data that was collected, these field data provided more opportunities for comparison between the experimental crop and the modelled crop than was available for past calibrations. Data from highly irrigated fields that experienced little water stress were used to calibrate the model, and the remaining deficit irrigation field data were used exclusively for verification of the calibrated model. The parameter values chosen in the final calibration were used in further irrigation simulation experiments. These were

conducted over a testing range for four separate irrigation strategies to determine what minimum irrigation amount would yield the maximum yield and which strategy is the most efficient. The DSSAT CROPGRO-Cotton model demonstrated potential to simulate the effects of various irrigation strategies on cotton yield, and the 12mm, 7.5 hr Time Temperature Threshold strategy was found to be the strategy to achieve a maximized yield with the greatest water use efficiency.

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All other work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

ARS	Agricultural Research Service
CSM	Cropping System Model
DAP	Days After Planting
DI	Daily Irrigation
DSSAT	Decision Support System for Agrotechnology Transfer
ET	Evapotranspiration
MAPE	Mean Absolute Percent Error
PRMSE	Percent Root Mean Square Error
TTT	Time Temperature Threshold
USDA	United States Department of Agriculture

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CHAPTER I

INTRODUCTION & LITERATURE REVIEW

1.1 General Background

The Texas High Plains form a unique region that has been a vital part of U.S. grain and fiber production for many decades. The region produces approximately 2/3 of the cotton in Texas, which is the foremost state in the nation for cotton production (Lubbock Chamber of Commerce, n.d.). It is a semi-arid region and lacks sufficient surface water sources to supply for its water demand (Colaizzi, Gowda, Marek, & Porter, 2009). The Ogallala Aquifer, upon which agriculture in the High Plains relies (Figure 1), spans portions of eight states. The water level in this aquifer is decreasing unevenly with greater changes observed in southern regions (Winter & Foster, 2014). According to a U.S. Geological Survey report, the greatest average change in water level from 2013-2015 was experienced by Texas, with a loss of approximately 0.5 m (McGuire, 2017). The Ogallala Aquifer supplies approximately 80% of the over 8.5 billion cubic meters of water withdrawn from Texas aquifers on an annual basis for the purpose of irrigation (George, Mace, & Petrossian, 2011). Texas law enables groundwater conservation districts to set a limit on groundwater pumping (Mace, Petrossian, Bradley, Mullican, & Christian, 2008; 79th Texas Legislature, 2005), so those living and investing in the Texas High Plains are beginning to experience the effects of conflicting interests in a diminishing water source. In October of 2016, a new Desired Future Condition was adopted for the Ogallala Aquifer which outlines an average drawdown of 7.0-8.2 m for the 2012 to 2070 period (Llano

Estacado UWCD, 2016). Although this does not yet affect consumers, proposals have been made to limit the quantity of water withdrawn from the Ogallala Aquifer for irrigation purposes. This is of particular concern to those who are financially dependent on agriculture. In response to this pending issue, new irrigation strategies that are aimed at reducing irrigation water use and increasing water use efficiency are being explored. Crop growth models, such as the Decision Support System for Agrotechnology Transfer (DSSAT), allow researchers to conduct several hypothetical irrigation experiments rapidly and inexpensively, facilitating the development and evaluation of water-efficient strategies.

Figure 1. The Ogallala Aquifer spans portions of eight states and lies under the shaded region of the Texas High Plains.

1.2 The DSSAT Model

DSSAT is a crop modeling software (Hoogenboom, et al., 2015) that uses meteorological, soil, and field experimental data to predict the growth and development of a particular crop in a set location. DSSAT has over 42 crop modules, each of which is designed to mimic the behavior of a specific crop. Cropping System Model (CSM), CROPGRO-cotton (Jones, et al., 2003) is the module which was used in this modelling research. Although previous research in the Texas High Plains and neighboring Texas Rolling Plains regions has addressed the calibration of CSM CROPGRO-Cotton (Adhikari, et al., 2016; Modala, et al., 2015), limited in-season crop data were used for model calibration in those studies. Since DSSAT is designed to model crop growth, this is an important aspect of model calibration that is overlooked when calibrating with solely yield data.

1.3 The USDA-ARS Field Study

An unpublished 2008 field study performed by the United States Department of Agriculture Agricultural Research Service (USDA-ARS) provides many more opportunities for comparison between the experimental crop and the modelled crop than was available for these past calibrations due to the wealth of in-season data that were collected. For said study, a cotton field in Lubbock, TX was subdivided into sections and these sections were subjected to different irrigation treatments. Two treatments were based on a time-temperature threshold, two were based on the daily rate of evapotranspiration, two received a consistent amount of water daily, and one was not irrigated. Throughout the growing season, the development of the plants in each field was monitored, and periodic measurements of growth indicators were taken until harvest. The raw experimental data from the irrigation study were shared with Texas A&M so that a model could be developed. The USDA study on the effects of different irrigation strategies on cotton yield serves as the basis of comparison for the DSSAT calibration in this study. With more points of reference, the calibrated model will be a more accurate reflection of what happens in the field throughout the cotton growing season. This is an opportunity to calibrate DSSAT in a way that takes advantage of its capabilities as a crop growth model.

1.4 Model Evaluation

By modifying the cultivar and ecotype files in DSSAT, the simulated growth and characteristics of a cotton crop can be redefined. The cultivar planted in the USDA ARS field, Deltapine 444, is an early maturing variety and there was no preexisting cultivar file entry that correctly modeled its growth, making calibration an essential step in the modeling process. Raw field data from the 2008 growth season were abundant; However, only three types of measurements were found to be comparable with DSSAT outputs. These were dry weight biomass, canopy height, and yield.

1.5 Past DSSAT Calibration Studies Referenced

One study which influenced the calibration methodology in this study was that of Adhikari, et al. (2016), which evaluated CSM CROPGRO Cotton for the Texas High Plains using the phenological stages of emergence, antithesis, and maturity as well as yield. The testing ranges and resulting variables used in the Adhikari et al. (2016) study served as guidelines for many of the variable testing ranges used to perform this Texas High Plains evaluation.

Another study by Modala, et al. (2015), used phenological stages, in-season data, and yield data in a similar evaluation of DSSAT for cotton. The corresponding field experiment was conducted in the Texas Rolling Plains region, which neighbors the Texas High Plains. In-season data that were available from the study for canopy height, number of nodes, and leaf area index were utilized in the model calibration and validation. A deficit irrigation scenario study was conducted for an evapotranspiration replacement strategy based on the calibrated model.

1.5 Objectives

The main objectives of this research are to:

1) Calibrate the DSSAT CSM CROPGRO-cotton model for the USDA's experimental cotton field.
    a) Choose variable values which produce simulated results most closely matching the in-season plant height, biomass, and yield data for unstressed zones during calibration.
    b) Verify this calibration with a comparison of the remaining data from the deficit irrigation zones with the simulated model results.
2) Use the calibrated model to assess the impact of irrigation amount and timing on crop yield.
    a) Determine the lowest irrigation amount that can be applied to maximize yield for each strategy.

b) Determine which of the studied irrigation strategies is the most efficient in achieving the maximization of yield.

CHAPTER II

METHODOLOGY

This chapter begins with the methodology for the field study from which the measured data used in the model calibration were derived. The second, third, and fourth sections cover the adjustment and evaluation of the model to reach a reasonable calibration. The final section outlines the methodology that was used in the simulated irrigation experiment.

2.1 Field Study

Comparison points for calibrating the DSSAT CSM CROPGRO-Cotton were based upon data collected from a field study conducted at the USDA-ARS Cropping Systems Research Laboratory in Lubbock, TX, under the direction of Dr. Dennis Gitz. The experimental crop of Deltapine 444 cotton was planted on June 2, 2008. There were seven zones (Figure 2), each of which consisted of 8 east-west oriented rows with a spacing of 101.6 cm. Each zone was composed of three 30.5 m long sections (i.e. East, Middle, and West). All zones were furrow irrigated 9 days after planting. Any further irrigation was delivered via the drip tape beneath each row from a metered pumping network (Figure 3). An overview of the irrigation strategies can be found in Table 1. Samples were only taken from the middle two rows of each zone to avoid interference from the neighboring zones’ irrigation regimes.

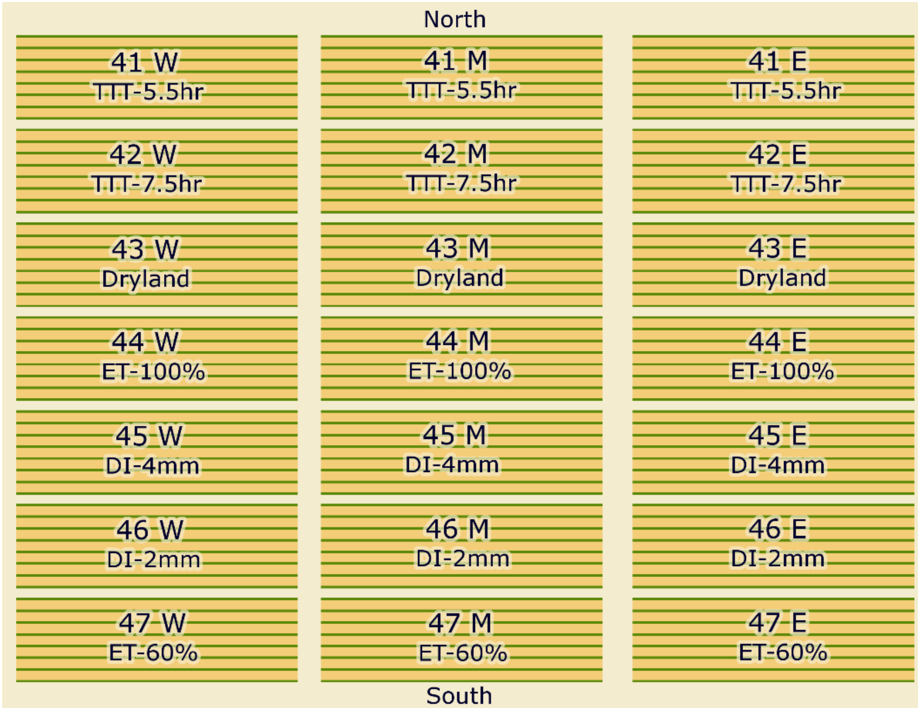

Figure 2. Diagram of Plot Layout for Experimental Field in Lubbock, TX.

Figure 3. Valve Hub Used to Deliver Specified Irrigation Amounts to Drip Feeds in Experimental Field.

Table 1. Description of Irrigation Scheduling Strategies for Seven Zones Used in the DSSAT Model Evaluation.

Zone		Irrigation Strategy Description[A]	Total Water Applied (mm)
High Water	TTT-5.5hr	Received 5 mm of water when temperature exceeds 28°C over a period of 5.5 hr or longer in the previous 24 hr	185.8
	ET-100	Received amount of water equivalent to the calculated evapotranspiration for the previous 24 hr	315.0
	DI-4mm	Received 4 mm of water daily	242.8
Deficit	TTT-7.5hr	Received 5 mm of water when temperature exceeds 28°C over a period of 7.5 hr or longer in the previous 24 hr	110.8
	ET-60	Received amount of water equivalent to 60% of the calculated evapotranspiration for the previous 24 hr	208.5
	DI-2mm	Receives 2 mm of water daily	122.8
	Dryland	Received no drip irrigation	50.8

[A] Irrigation was not applied during days on which the rainfall override was triggered due to a sensed precipitation event.

To collect a canopy height record, a meter stick was held at the soil line and the measure from base to terminal was recorded in centimeters to the nearest tenth. To create a comparison point, the average value was calculated from the 6-8 measurements taken on each of 21 monitored days spaced throughout the growing season. To collect a plant biomass record, plants were harvested and oven dried at 60-65°C for a minimum of 48 hr. The dry weight of the plant was recorded at various growth stages. To create a comparison point, the average biomass was calculated for the measurements taken on each of the monitored days spaced throughout the growing season. To create an equivalent point from the DSSAT output, it was necessary to combine the leaf, stem, and pod dry weights into a total plant biomass. Yield was measured as the combined seed and lint weight from two meters of hand harvest. To create a comparison point, the average of the three samples collected from each zone was calculated.

A daily record of the amount of irrigation water each zone received via the drip tape irrigation system was provided by the USDA-ARS. Information on the soil profile is not available for the experimental field. Instead, a soil profile (Table 2) was developed based on the soil type, Amarillo Fine Sandy Loam (SOILWEB, site saying urban is mostly concrete and AFSL).

The soil horizon designation (SLMH), saturated hydraulic conductivity (SSKS), bulk density (SBDM), organic carbon percentage (SLOC), clay percentage (SLCL), silt percentage (SLSI), pH by water extraction (SLHW), and cation exchange capacity (SCEC) were obtained and calculated from National Cooperative Soil Survey data accessed through SoilWeb, an online application maintained by the California Soil Resource Lab at the University of California, Davis. The lower limit of extractable water (SLLL), drained upper limit (SDUL) saturated upper limit (SSAT) were approximated as the water retained at -15 bar, water retained at -0.33 bar, and effective porosity, respectively, based on the soil texture for each layer as calculated by Rawls et al. (1982). The Munsell soil color of 7.5YR (NCSS, 2016) corresponded to a value of 0.13 for the albedo ratio (Gijsman, Thornton, & Hoogenboom, 2007). While the soil was classified as well drained (NCSS, n.d.), a more conservative drainage rate of 0.4 was used (Gijsman, Thornton, & Hoogenboom, 2007). The soil was categorized as hydrologic group B (NCSS, n.d.), which corresponds to a runoff curve number of 78 for straight row, cultivated agricultural land in good condition (NRCS, 1986).

Table 2. Modified Soil Data Used in DSSAT Simulation.

Base Depth (cm)	SLMH	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLHW	SCEC
5	Ap	0.095	0.207	0.412	0.7	10.1	1.53	0.9	15	16	7.5	13.6
15	Ap	0.095	0.207	0.412	0.684	10.1	1.53	0.9	15	16	7.5	13.6
26	Ap	0.095	0.207	0.412	0.55	10.1	1.53	0.9	15	16	7.5	13.6
45	Bt	0.148	0.255	0.33	0.427	3.2	1.64	0.5	25	17	7.6	19.4
60	Bt	0.148	0.255	0.33	0.299	3.2	1.64	0.5	25	17	7.6	19.4
103	Bt	0.148	0.255	0.33	0.066	3.2	1.64	0.5	25	17	7.6	19.4
120	Btkk	0.148	0.255	0.33	0.066	3.2	1.58	0.15	34	19	8.3	12.2
142	Btkk	0.148	0.255	0.33	0.016	3.2	1.58	0.15	34	19	8.3	12.2
180	Btk	0.148	0.255	0.33	0.05	3.2	1.61	0.2	30	18	8.1	16.5
210	Btk	0.148	0.255	0.33	0	3.2	1.61	0.2	30	18	8.1	16.5

Weather data records were procured from the on-site Plant Stress & Water Conservation Meteorological Tower. Daily data for precipitation, wind speed, average relative humidity, minimum temperature, maximum temperature, solar radiation, and pan evaporation were compiled in Excel. The tools used to collect these data are listed in Table 3. Information for three days, in total, was missing from this data set, so supplementary precipitation, temperature, solar radiation, and wind speed data were retrieved from the Lubbock 3WNW-TTU weather station, which is part of the West Texas Mesonet (West Texas Mesonet, 2008). Solar radiation daily averages for the 10th through 144th days of 2008 were also replaced using data from the 3WNW-TTU station located less than 1.2 km from the field. The mean and median of the new values were far more congruent with the rest of the data at 227 W m^{-2} and 220 W m^{-2}, respectively. The raw data were then imported into WeatherMan, a meteorological data processing application designed for use with crop modelling software. Using this application, the data were formatted and exported for use in DSSAT. A summary of the most critical weather factors for the months of June through September can be found in Table 4.

Table 3. Overview of tools used to collect meteorological data on site. Adapted from tables provided by Dr. J.E. Stout of the USDA-ARS (Stout, 2016).

Measurement	Model	Information
Precipitation	Texas Electronics #TE525	Tipping bucket, 1 mm per tip
Wind Speed	R.M. Young #05103	Propeller type, A.C. sine wave, Distance constant 2.7 m
Relative Humidity & Temperature	CS500	Vaisala INTERCAP Capacitance RH Sensor, Platinum Resistance Temperature Detector
Solar Radiation	LI-COR #LI-200SZ	Pyranometer
Pan Evaporation	255-100 Novalynx Evaporation Gauge	Stainless steel pan with analog output

Table 4. Summary of Solar Radiation, Temperature, and Precipitation Data for the months of June-November.

Month	Average Daily Solar Radiation ($W\ m^{-2}$)	Average Daily Maximum Temperature (℃)	Average Daily Minimum Temperature (℃)	Total Precipitation (mm)
June	323.6	32.1	20.4	115
July	285.1	34.4	21.4	84
August	265.6	35.6	22.6	11.3
September	222.1	29.7	18.6	50.5
October	173.2	23.8	8.7	71.1
November	156.1	19.2	3.1	3

2.2 Phenological Stages

An adjustment of DSSAT growth stage outputs to comparable phenological stages from the field experiment and other sources (Kerns, Sansone, Siders, & Baugh, 2008; Deterling & El-Zik, 1982) was conducted prior to the main calibration of parameters. The ecotype parameters for time from planting to emergence (PL-EM) and time from planting to first leaf (EM-V1), as well as the cultivar parameter for time from emergence to flower appearance (EM-FL), were all modified and set before continuing with the main calibration. Throughout calibration, the growth stages were monitored to ensure that they remained within the documented ranges from literature.

2.3 Model Calibration

Calibration of the model was achieved by comparing the experimental results of the TTT-5.5hr, ET-100, and DI-4mm high water treatments to the model results for plant height and biomass throughout the season as well as the final yield. With complete data only available for the year of 2008, the application of many widely used statistical calibration indicators was limited by the lack of sequential data, so calibration efforts were primarily directed by the minimization of two error indicators, mean absolute percentage error (MAPE, eq. 1) and percentage root-mean-square error (PRMSE, eq. 2), with a target of 20% or lower MAPE. In the case of yield comparisons an absolute percent error (APE, eq. 3) calculation was used, to more clearly portray a single point comparison. For each of the canopy height and biomass comparisons, a coefficient of determination (r^2, eq. 4) was calculated.

The formulae are as follows:

$$MAPE = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{y_{m,i} - y_{s,i}}{y_{m,i}} \right| \quad (1)$$

$$PRMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_{s,i} - y_{m,i})^2}{n}} * \frac{100 * n}{\sum_{i=1}^{n} y_{m,i}} \quad (2)$$

$$APE = \frac{y_{m,i} - y_{s,i}}{y_{m,i}} \quad (3)$$

$$r^2 = \left(\frac{\sum_{i=1}^{n} (y_{m,i} - \bar{y}_m)(y_{s,i} - \bar{y}_s)}{\sqrt{\sum_{i=1}^{n} (y_{m,i} - \bar{y}_m)^2 \sum_{i=1}^{n} (y_{s,i} - \bar{y}_s)^2}} \right)^2 \quad (4)$$

Where

y_s = Simulated value

$\bar{y}_s$ = Average of simulated values in data set

y_m = Measured value

$\bar{y}_m$ = Average of measured values in data set

n = Total number of samples

Eleven cultivar parameters and one ecotype parameter used by DSSAT were individually adjusted across a testing range for each iteration (Table 5). The testing range was chosen based on both a previous Texas High Plains cotton calibration study (Adhikari, et al., 2016) and observation of values for other preexisting cultivars in DSSAT. This was performed in a systematic fashion, finalizing the value of the first parameter and continuing to the next in the listed order (Table 5) until all variables were finalized. Iterations were performed with the goal of identifying the value which minimized error in plant height, biomass, and yield predictions. The simulated growth stages were compared with the corresponding observed occurrences and acceptable date ranges for cotton grown in the same region as a final check to ensure that the values are reasonable.

Table 5. Parameters modified in calibration process as described in the DSSAT cotton cultivar file, accompanied by testing range and smallest increment of modification. To determine the ideal values, several simulation iterations were performed for each individual parameter by varying its value within the proposed testing range.

Parameter	Testing Range	Increment Precision	DSSAT Description
Cultivar Parameters			
FL-SH	6-12	1	Time between first flower and first pod (R3) (photothermal days)
FL-SD	12-20	1	Time between first flower and first seed (R5) (photothermal days)
SD-PM	35-40[A]	1	Time between first seed (R5) and physiological maturity (R7) (photothermal days)
FL-LF	60-80	1	Time between first flower (R1) and end of leaf expansion (photothermal days)
LFMAX	1-1.3	0.01	Maximum leaf photosynthesis rate at 30 °C, 350 ppm CO_2, and high light (mg CO_2 m^{-2} s^{-1})
SLAVR	165-180	1	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})
SIZLF	250-320	1	Maximum size of full leaf (three leaflets) (cm^2)

Table 5 Continued

Parameter	Testing Range	Increment Precision	DSSAT Description
XFRT	0.5-0.9	0.01	Maximum fraction of daily growth that is partitioned to seed + shell
SFDUR	33-36	1	Seed filling duration for pod cohort at standard growth conditions (photothermal days)
PODUR	8-14	1	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)
THRSH	65-75	1	Threshing percentage. The maximum ratio of (seed/(seed + shell)) at maturity.
Ecotype Parameter			
FL-VS	40-75	1	Time from first flower to last leaf on main stem (photothermal days)

[A] The upper limit of this testing range was set due to its effect on phenological growth stages.

2.4 Model Validation

Once an ideal combination of variable values was identified, the accuracy of the calibrated model was verified by comparing the simulated values for the deficit irrigation plots, TTT-7.5hr, ET-60, DI-2mm, and Dryland, against the experimental values, which were not used during calibration. This was completed using the same error indicators employed in the calibration comparisons, MAPE and PRMSE, with a target of 20% or lower MAPE.

2.5 Irrigation Scenario Comparison

After successful calibration and validation of the model, it was then possible to use it as a tool to determine what comparative yields would be under varying irrigation amounts. Using the four unique irrigation strategies from the field study--TTT 5.5hr, TTT7.5hr, Daily Irrigation, and ET Replacement--scenarios were developed which varied the amount of water applied for each irrigation event. The yield trend for each strategy was graphed and evaluated to determine whether the yield had reached a stable maximum value. If not, the range was extended, the final details of which can be found in Table 6. The yield maximum was determined to be the last point for which the yield result increased by more than 1% of the previous result.

Simulations were designed to represent consistent initial conditions, those of zone 41 in the field study. Irrigation was scheduled exactly as it was recorded in the field study, which did not supply water during days on which rainfall override was triggered by a sensed precipitation event.

Table 6. Simulation Testing Range Details for Four Unique Irrigation Treatment Strategies.

Strategy	Testing Range	Increment
TTT 5.5hr	2.0-8.0 mm	0.5 mm
TTT 7.5hr	2.0-15.0 mm	0.5 mm
Daily Irrigation	2.0-6.0 mm	0.5 mm
ET Replacement	50-110%	5.0%

The irrigation water use efficiency was calculated using equation 5 for each simulation in the testing range. Comparisons were made against a baseline scenario which used the same initial conditions as the other simulations in the testing range. The irrigation schedule for the baseline scenario was modeled after that of the Dryland zone in the field experiments, which received only one initial furrow irrigation of 50.8 mm to encourage seed germination.

$$IWUE = \frac{Y_i - Y_d}{AW_i - AW_d} \tag{5}$$

Where:

$IWUE$ = Irrigation Water Use Efficiency (kg/m^3)

Y_i=Yield of irrigated field (kg/ha)

Y_d=Yield of dryland field (kg/ha)

AW_i=Applied water total for irrigated field (mm)

AW_d=Applied water total for dryland field (mm)

CHAPTER III

RESULTS & DISCUSSION

Chapter three covers the calibration and validation results in the first two sections. The tables and figures in the sub-sections reflect comparisons of the measured field data and the outputs simulated by DSSAT using the final parameter values. The third and final section is reserved for the results of the irrigation experiment that was conducted using the evaluated model.

3.1 Model Calibration

The performance of the model was improved upon as much as possible while remaining in accordance with the methodology. At the end of the systematic calibration process for the twelve adjusted parameters, the values which produced the minimum error were recorded as final. They are shown in Table 7.

Table 7. Final Values of DSSAT Parameters Resulting from Calibration.

Parameter	DSSAT Description	Final Value
FL-SH	Time between first flower and first pod (R3) (photothermal days)	6
FL-SD	Time between first flower and first seed (R5) (photothermal days)	12
SD-PM	Time between first seed (R5) and physiological maturity (R7) (photothermal days)	40
FL-LF	Time between first flower (R1) and end of leaf expansion (photothermal days)	70
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 ppm CO_2, and high light (mg CO_2 m^{-2} s^{-1})	1.3
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	165
SIZLF	Maximum size of full leaf (three leaflets) (cm^2)	320
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.9
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	36
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	8
THRSH	Threshing percentage. The maximum ratio of (seed/(seed + shell)) at maturity.	70
FL-VS	Time from first flower to last leaf on main stem (photothermal days)	42

3.1.1 Phenological Stage Calibration

A reasonable match between the timing of growth stages simulated by DSSAT and the emergence and flowering dates recorded from the field study was found (Table 8). The stages for all of the simulations fell within an acceptable range for cotton grown in the Texas High Plains region. This was achieved by setting PL-EM to 3, EM-V1 to 3, and EM-FL to 38 prior to continuing with the calibration. During the calibration, it was deemed necessary to cap the upper limit of the testing range for SD-PM at 40 to maintain a physiological maturity date within the targeted range. The dates for emergence and flowering that were recorded in the field study came sooner than the corresponding mean dates from literature (Deterling & El-Zik, 1982; Kerns, Sansone, Siders, & Baugh, 2008); this can be attributed to the early maturity of the Deltapine 444 cultivar.

Table 8. Target Values for Emergence, First Leaf, Flowering, and Physiological Maturity Development Stages and DSSAT Simulated Results for All Treatments.

Growth Stage	Targeted Days After Planting				Calibration			Validation			
	Min	Max	Mean	Field	TTT-5.5hr	ET-100	DI-4mm	Dryland	DI-2mm	ET-60	TTT-7.5hr
Emergence	5[A]	20[A]	10[A]	5	5	5	5	5	5	5	5
First Leaf	11[B]	25[B]	16[B]		11	11	11	11	11	11	11
Flowering	45[C]	81[C]	61[C]	52	52	52	52	52	52	52	52
Physiological Maturity	120[D]	150[D]	140[D]		147	149	149	140	142	147	141

[A] Days from planting to emergence (Deterling & El-Zik, 1982)
[B] Days from planting to first true leaf (Kerns, Sansone, Siders, & Baugh, 2008)
[C] Days from planting to first bloom (Kerns, Sansone, Siders, & Baugh, 2008)
[D] Growing season for High Plains region (Deterling & El-Zik, 1982)

3.1.2 Biomass Calibration

Results for the MAPE, the PRMSE, and the coefficient of determination of the calibration treatments are listed in Table 9, with an average MAPE of 18.1%, PRMSE of 28.7%, and r^2 of 0.88. The individual biomass graphs for each treatment are shown in Figures 4-6. The target MAPE of 20% or less was exceeded by 1.6% for the DI-4mm treatment. In general, the measured and simulated data were in agreement up until approximately 113 days after planting (DAP). In the subsequent days, it is presumed that the natural progression of senescence was not reflected as strongly in the simulated biomass data. This difference is particularly prominent in the DI-4mm treatment.

Table 9. MAPE and PRMSE Error Indicator Results for Biomass Data from TTT-5.5hr, ET-100, and DI-4mm Calibration Treatments.

Treatment	MAPE	PRMSE	r^2
TTT-5.5hr	17.6	23.6	0.92
ET-100	15.0	30.5	0.91
DI-4mm	21.6	31.9	0.82
Average	18.1	28.7	0.88

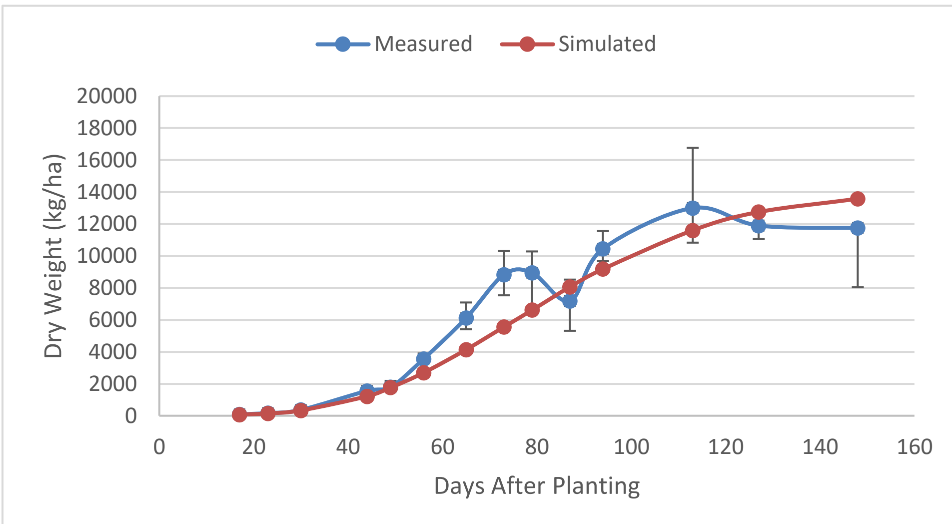

Figure 4. Comparison of Measured Biomass Dry Weight to Simulated Biomass Dry Weight for TTT-5.5hr Calibration Treatment. Biomass Includes Stem, Leaf, and Pod Components. Error Bars Represent the Minimum and Maximum Measured Values.

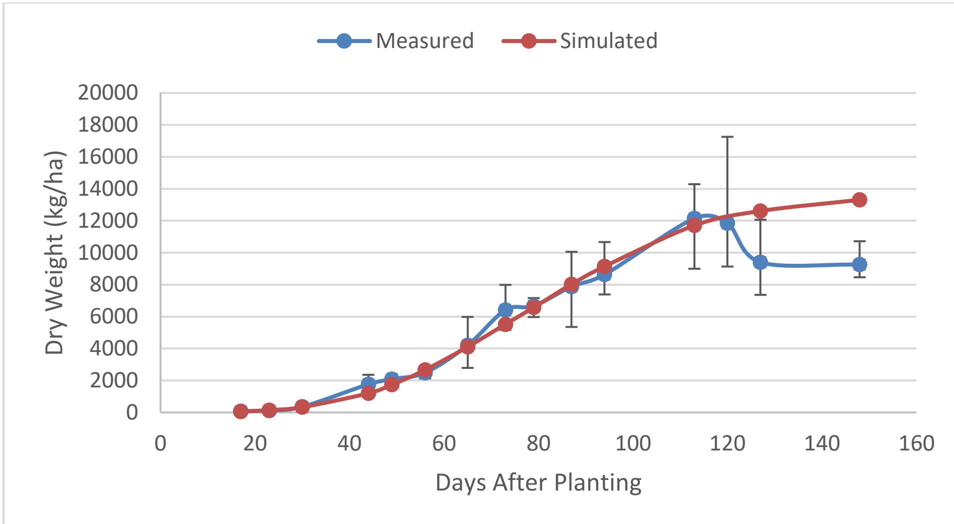

Figure 5. Comparison of Measured Biomass Dry Weight to Simulated Biomass Dry Weight for ET-100 Calibration Treatment. Biomass Includes Stem, Leaf, and Pod Components. Error Bars Represent the Minimum and Maximum Measured Values.

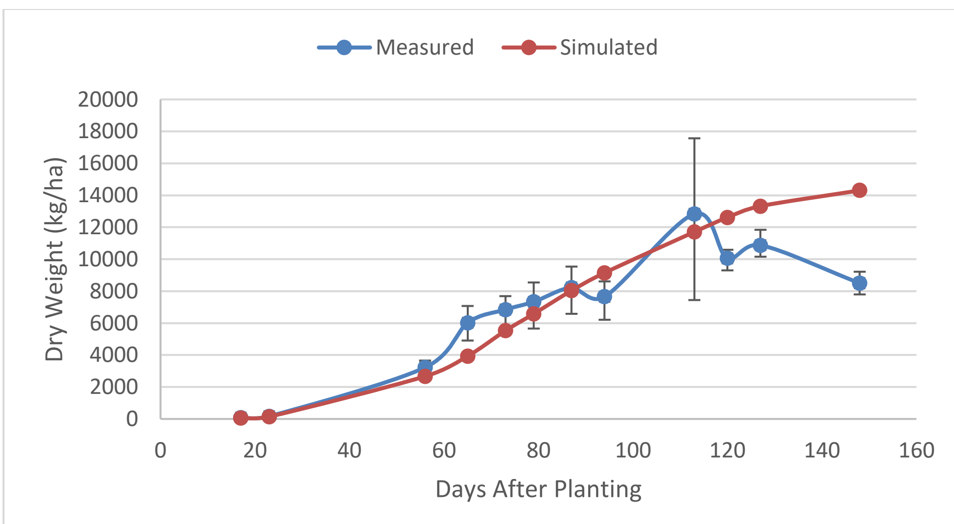

Figure 6. Comparison of Measured Biomass Dry Weight to Simulated Biomass Dry Weight for DI-4mm Calibration Treatment. Biomass Includes Stem, Leaf, and Pod Components. Error Bars Represent the Minimum and Maximum Measured Values.

3.1.3 Canopy Height Calibration

Canopy height data were only collected for two of the calibration treatments, TTT-5.5hr and ET-100. The resulting MAPE, PRMSE, and coefficient of determination are shown in Table 10. The average MAPE is 14.8%, PRMSE is 16.1%, and r^2 is 0.82. The r^2 value is not as high as some values achieved for calibration treatments in literature (Modala, et al., 2015) but still reasonably close to 1. The canopy height graphs for each treatment are shown in Figures 7 and 8.

Table 10. MAPE and PRMSE Error Indicator Results for Canopy Height Data from TTT-5.5hr and ET-100 Calibration Treatments.

Treatment	MAPE	PRMSE	r^2
TTT-5.5hr	10.4	11.1	0.86
ET-100	19.2	21.1	0.77
Average	14.8	16.1	0.82

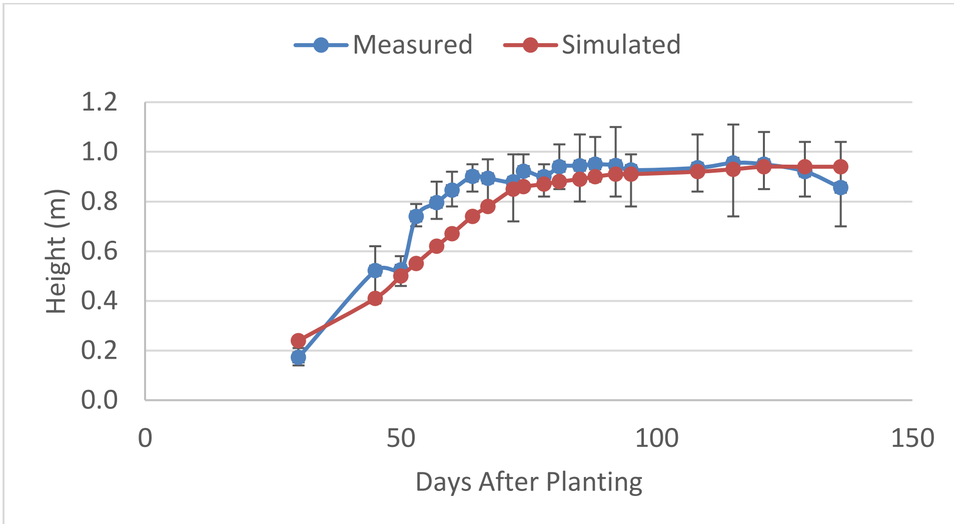

Figure 7. Comparison of Measured Canopy Height to Simulated Canopy Height for TTT-5.5hr Calibration Treatment. Error Bars Represent the Minimum and Maximum Measured Values.

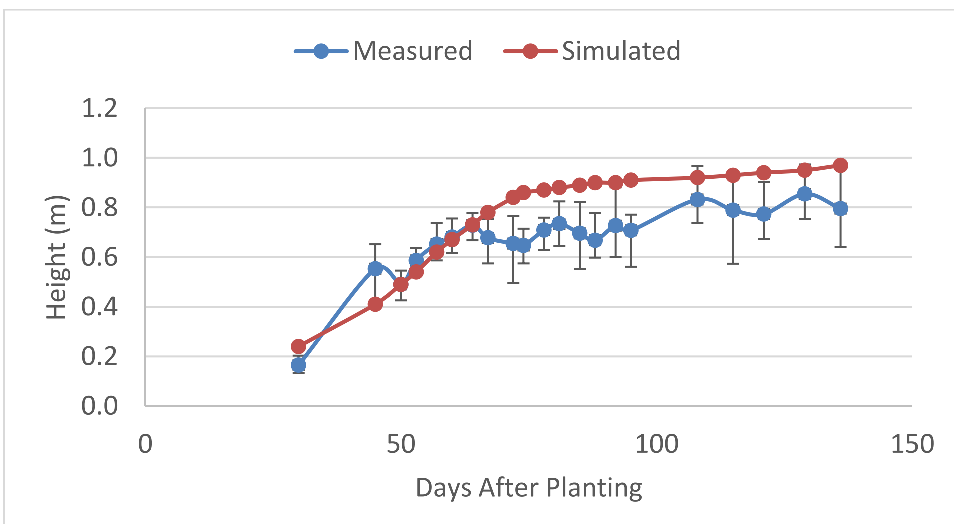

Figure 8. Comparison of Measured Canopy Height to Simulated Canopy Height for ET-100 Calibration Treatment. Error Bars Represent the Minimum and Maximum Measured Values.

3.1.4 Yield Calibration

Results for yield comparisons are located in Table 11. Since the yield measurement is only taken once in the season, the absolute percentage error for each strategy is also listed in addition to the MAPE. The simulated results were plotted in concurrence with a bar graph representing the measured yield data for each treatment (Figure 9). These results were a close match during calibration, as indicated by very low APE values.

Table 11. Average Percent Error and MAPE for Calibration Treatment Yields from TTT-5.5hr, ET-100, and DI-4mm.

Treatment	Measured (kg/ha)	Simulated (kg/ha)	APE
TTT-5.5hr	6238	6246	0.134
ET-100	6522	6539	0.255
DI-4mm	6994	6541	6.48
		MAPE	2.29

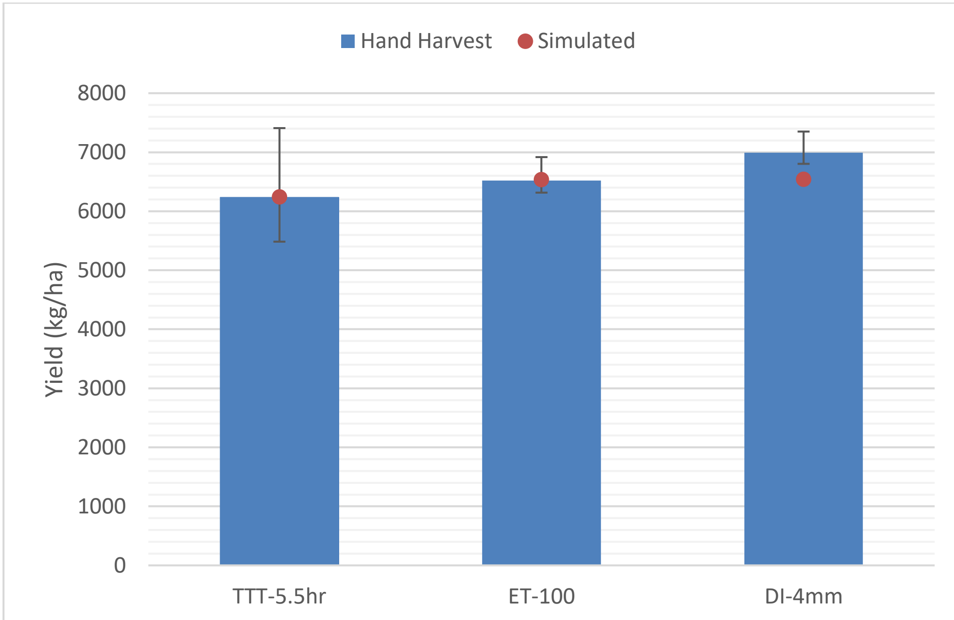

Figure 9. Comparison of Hand Harvested Yield to Simulated Yield for TTT-5.5hr, ET-100, and DI-4mm Calibration Treatments. Yield Includes the Weight of Both Lint and Seed Components. Error Bars Represent the Minimum and Maximum Measured Values.

3.2 Model Validation

3.2.1 Biomass Validation

Results for the biomass MAPE, PRMSE, and coefficient of determination for the validation treatments can be found in Table 12. They produced an average MAPE of 18.1%, PRMSE of 28.7%, and r^2 of 0.90. The individual biomass graphs for each treatment are shown in Figures 10-13.

Table 12. MAPE and PRMSE Error Indicator Results from Biomass Data for TTT-7.5hr, ET-60, DI-2mm, and Dryland Validation Treatments.

Treatment	MAPE	PRMSE	r^2
TTT-7.5hr	11.3	17.6	0.95
ET-60	19.0	25.3	0.84
DI-2mm	15.1	22.9	0.85
Dryland	12.8	16.8	0.95
Average	14.6	20.6	0.90

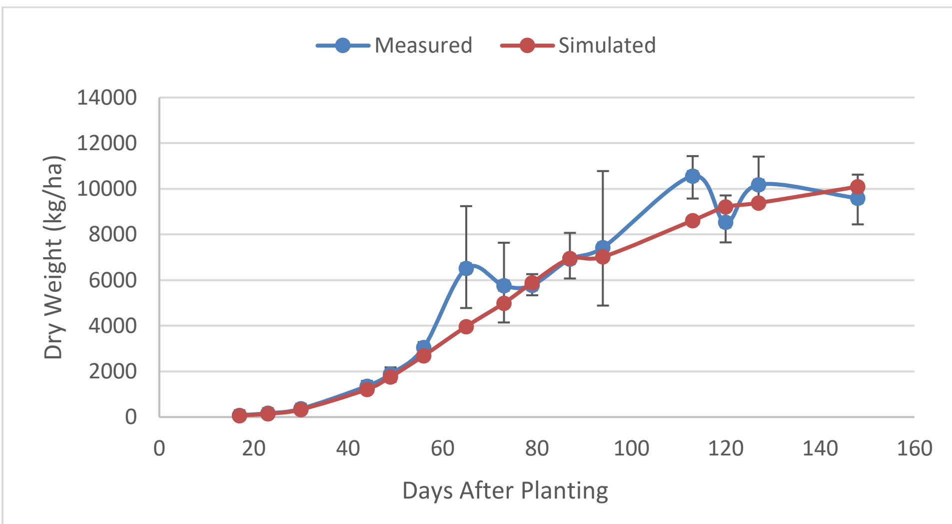

Figure 10. Comparison of Measured Biomass Dry Weight to Simulated Biomass Dry Weight for TTT-7.5hr Validation Treatment. Biomass Includes Stem Leaf and Pod Components. Error Bars Represent the Minimum and Maximum Measured Values.

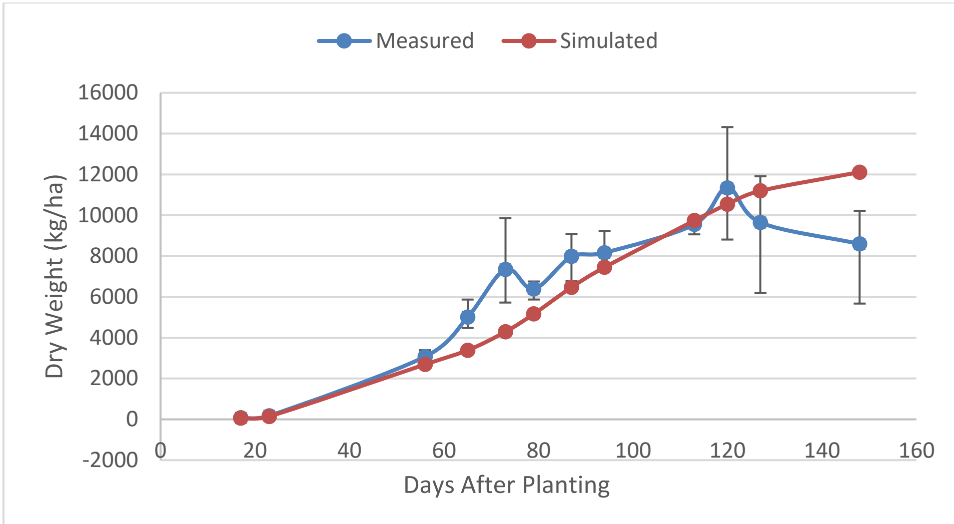

Figure 11. Comparison of Measured Biomass Dry Weight to Simulated Biomass Dry Weight for ET-60 Validation Treatment. Biomass Includes Stem Leaf and Pod Components. Error Bars Represent the Minimum and Maximum Measured Values.

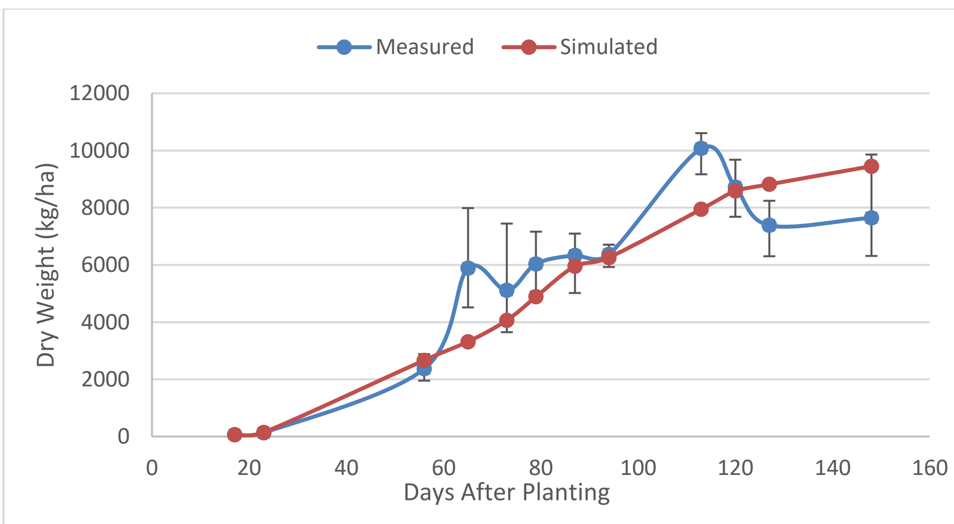

Figure 12. Comparison of Measured Biomass Dry Weight to Simulated Biomass Dry Weight for DI-2mm Validation Treatment. Biomass Includes Stem Leaf and Pod Components. Error Bars Represent the Minimum and Maximum Measured Values.

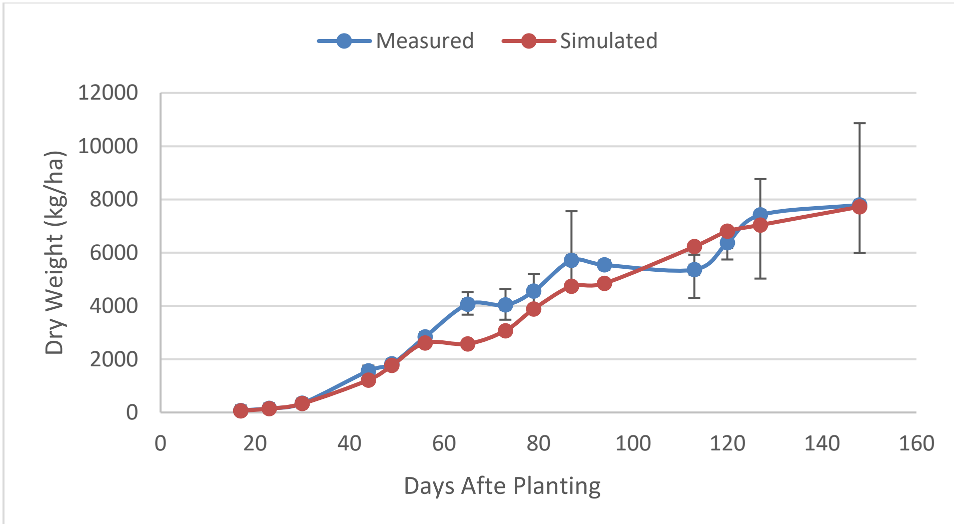

Figure 13. Comparison of Measured Biomass Dry Weight to Simulated Biomass Dry Weight for Dryland Validation Treatment. Biomass Includes Stem Leaf and Pod Components. Error Bars Represent the Minimum and Maximum Measured Values.

3.2.2 Canopy Height Validation

As was the case for calibration, canopy height data were only available for two of the validation treatments, TTT-7.5hr and Dryland. The MAPE, PRMSE, and coefficient of determination values resulting from these data sets can be found in Table 13. The average MAPE is 14.8%, PRMSE is 16.1%, and r^2 is 0.80. The canopy height graphs for each treatment are shown in Figures 14 and 15.

Table 13. MAPE and PRMSE Error Indicator Results from Canopy Height Data for TTT-7.5hr and ET-600 Validation Treatments.

Treatment	MAPE	PRMSE	r^2
TTT-7.5hr	13.2	13.5	0.88
Dryland	12.5	13.4	0.72
Average	12.8	13.4	0.80

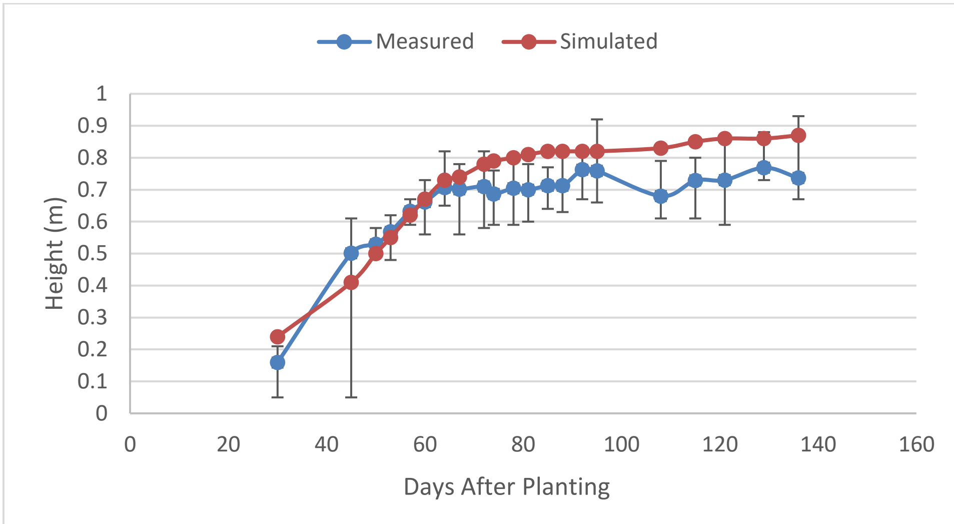

Figure 14. Comparison of Measured Canopy Height to Simulated Canopy Height for TTT-7.5hr Validation Treatment. Error Bars Represent the Minimum and Maximum Measured Values.

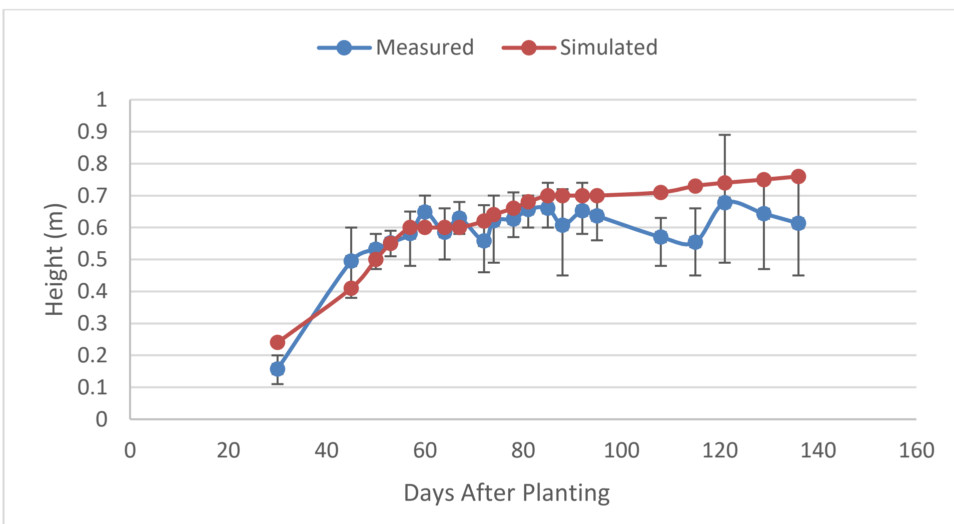

Figure 15. Comparison of Measured Canopy Height to Simulated Canopy Height for Dryland Validation Treatment. Error Bars Represent the Minimum and Maximum Measured Values.

3.2.3 Yield Validation

Table 14 shows the results from the yield comparisons. As was practiced for the calibration results, the absolute percentage error for each strategy is listed in addition to the MAPE. APE values for the validation treatments, especially the drier treatments, were higher than those achieved in calibration and exceeded those reported in similar studies, which generally ranged from 1-9% (Adhikari, et al., 2016; Modala, et al., 2015). Despite this, the MAPE for the validation treatments remained below 20% at 16.2%. The simulated results and the measured yield data for each treatment are graphed in Figure 16.

Table 14. Average Percent Error and MAPE of Validation Treatment Yields for TTT-7.5hr, ET-60, DI-2mm, and Dryland.

Treatment	Measured (kg/ha)	Simulated (kg/ha)	APE
TTT-7.5hr	5294	3947	25.4
ET-60	5585	5621	0.649
DI-2mm	5300	4277	19.3
Dryland	3150	2541	19.3
		MAPE	16.1

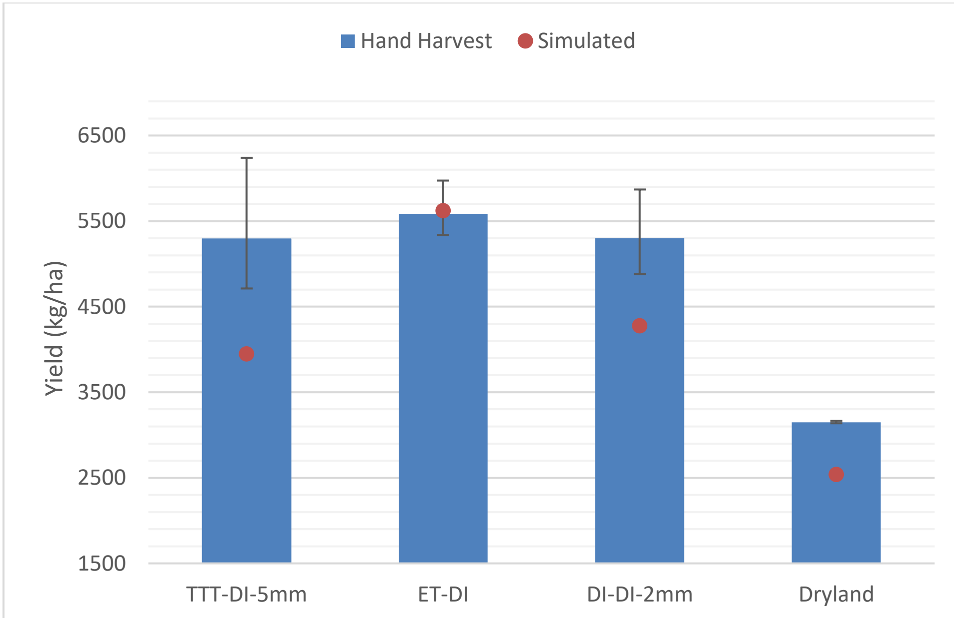

Figure 16. Comparison of Hand Harvested Yield to Simulated Yield for TTT-7.5hr, ET-60, DI-2mm, and Dryland Validation Treatments. Yield Includes the Weight of Both Lint and Seed Components. Error Bars Represent the Minimum and Maximum Measured Values.

3.3 Irrigation Scenario Comparison

The simulated yield and resulting IWUE are shown for the increments across the testing range for TTT-5.5hr, TTT-7.5hr, Daily Irrigation, and ET Replacement in Figures 17, 18, 19, and 20, respectively. The TTT-5.5hr experiment showed a steady rise in yield until it plateaued. The maximum yield was achieved at approximately 6 mm (Figure 17). The IWUE peaked at 4 mm and declined with each increase in water application thereafter.

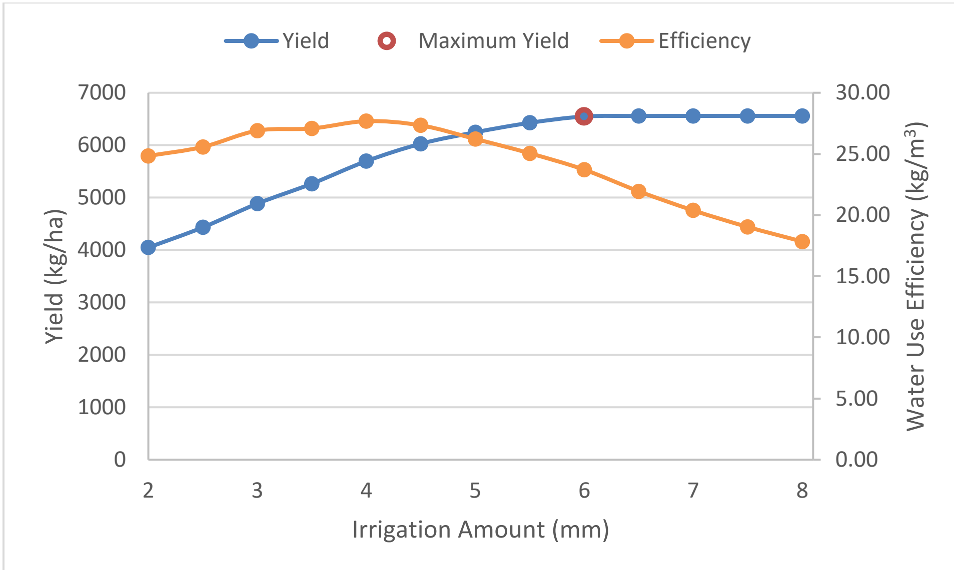

Figure 17. Graphs of Simulated Yield and Efficiency for TTT-5.5hr Experiment Across Testing Range of 2.0-8.0 mm.

Figure 18 captured a simulated maximum yield at 12 mm for the TTT-7.5hr experiment. The yield did not rise as steadily as it did for the other strategies, leading to a more erratic water use efficiency curve with a maximum at 2 mm and another peak at 9.5 mm. The start of the most consistent decline in efficiency was concurrent with the achievement of maximum yield.

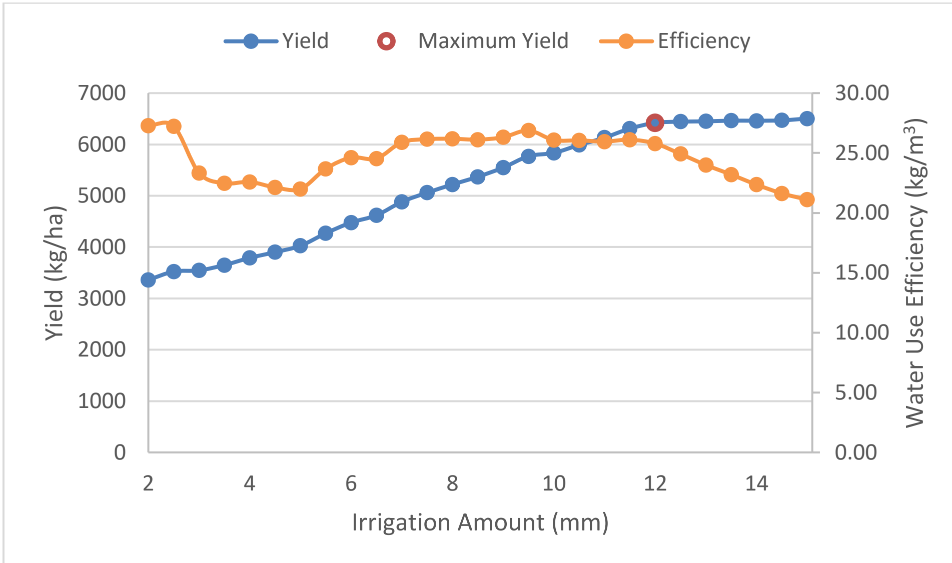

Figure 18. Graphs of Simulated Yield and Efficiency for TTT-7.5hr Experiment Across Testing Range of 2.0-15.0 mm.

Daily Irrigation resulted in a maximum yield at 4.5 mm (Figure 19). Until the maximum was reached, yield had been increasing steadily. The IWUE remained stable at approximately 25 kg m^{-3} before the beginning of a clear negative trend at 4 mm.

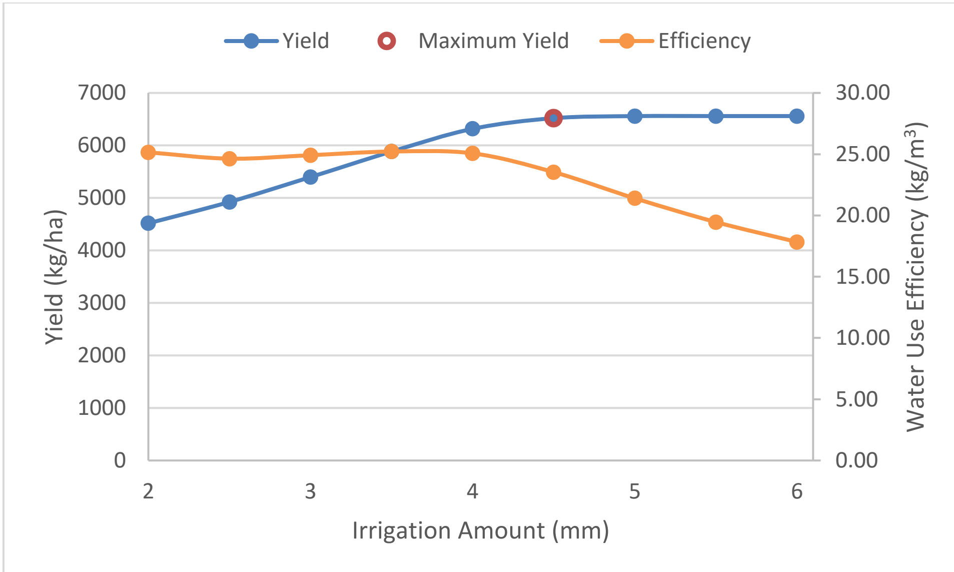

Figure 19. Graphs of Simulated Yield and Efficiency for Daily Irrigation Experiment Across Testing Range of 2.0-6.0 mm.

Results from the ET Replacement strategy simulations are recorded in Figure 20. Overall, there was a positive trend in yield until the maximum was reached at 95% replacement. The IWUE decreased with each increase in applied water with a small increase concurrent with the maximum yield, after which it decreased steadily.

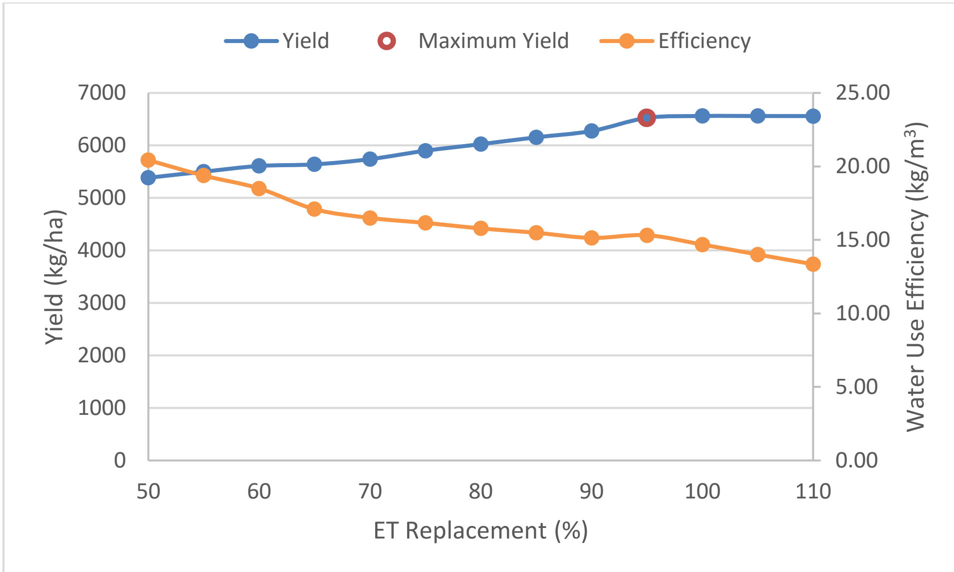

Figure 20. Graphs of Simulated Yield and Efficiency for ET Replacement Experiment Across Testing Range of 50-110%.

The yield was maximized at 6 mm for TTT-5.5hr, 12 mm for TTT-7.5hr, 4.5 mm for daily irrigation, and 95% for ET Replacement. Consequently, the IWUE trend continued to decline after that point for each of the strategies as the addition of more water no longer significantly increased the yield. The yield and efficiency for the maximized yield scenarios of each strategy are shown collectively in Figure 21.

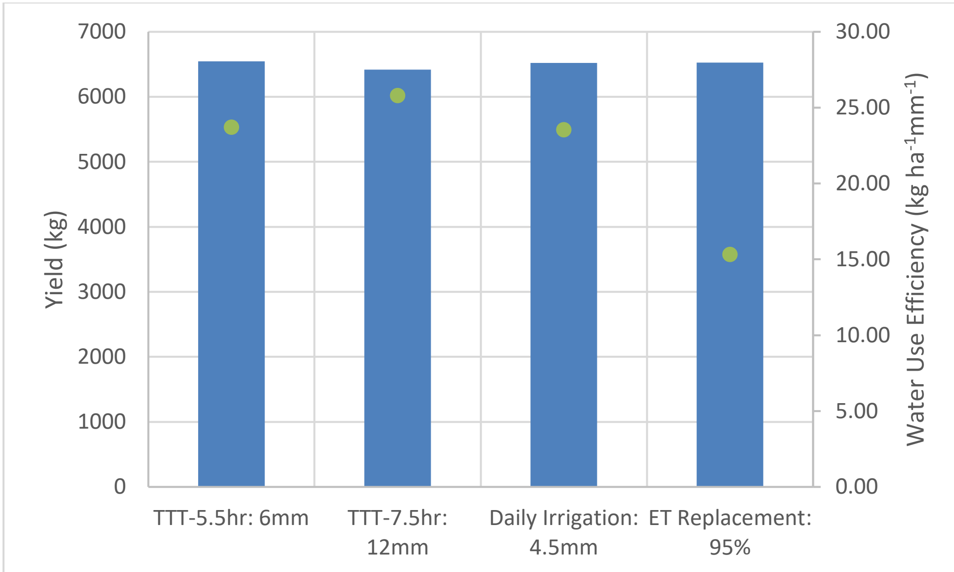

Figure 21. Graph of Yield and Efficiency of the Maximum Yield Scenario for Each of the Four Strategies. Efficiency Is Represented by a Points Corresponding to Each of the Yield Columns.

CHAPTER IV

SUMMARY OF FINDINGS & CONCLUSIONS

The in-season data available from the field study and the variety of irrigation strategies that were used provided extra dimensions in the evaluation of the DSSAT model. The Texas High Plains region, in which the study was conducted, is unique and vital to cotton production. The water shortages on the horizon increase the necessity of developing more efficient irrigation practices.

Crop growth models are valuable tools which enable experimentation with different procedures and treatments on a field without wasting tangible resources. Running a panel of simulations can be very useful in pinpointing an ideal scenario or set of conditions. This functionality was utilized as the model was run in the multi-scenario irrigation experiment.

The following conclusions were drawn based on this study:

1. DSSAT CROPGRO Cotton model demonstrated potential to accurately simulate experimental yields under various irrigation treatments.
2. The biomass, canopy height, and yield comparisons during calibration produced average MAPEs of 18.0%, 14.8% and 2.3% respectively. These were all below the 20% goal for average MAPE in each category. Even lower MAPEs were achieved for biomass and canopy height during validation. Unfortunately, error indicators for the yield of validation treatments did not produce superior results, but the average error for the validation treatments remained below 20% at 16.2%.

3. The TTT-7.5hr 12mm irrigation scenario was found to be the most efficient of the maximum yield scenarios, followed closely by DI-4mm and TTT-5.5hr-6mm, while ET-95% was the least efficient of the four.

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