# EVALUATION OF THE CSM-CROPGRO-COTTON MODEL FOR THE TEXAS ROLLING PLAINS REGION AND SIMULATION OF DEFICIT IRRIGATION STRATEGIES FOR INCREASING WATER USE EFFICIENCY

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**ABSTRACT.** *Cotton is one of the major crops cultivated in the Texas Rolling Plains region, and it is a major contributor to the regional economy. Cotton cultivation in this region is facing severe challenges due to an increase in the frequency of droughts and a projected decrease in rainfall in the future. Development and evaluation of deficit irrigation strategies for this region could potentially conserve water while maintaining cotton yields. In this study, the Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM) CROPGRO-Cotton was extensively tested and then used for evaluating various deficit irrigation strategies for this region. The model inputs were obtained from field experiments conducted at Chillicothe, Texas, during four growing seasons: 2008-2010 and 2012. The model was first calibrated using the data from a 100% evapotranspiration (ET) replacement irrigation scheduling experiment conducted in 2012 and then validated on three other irrigation scheduling treatments (75% ET replacement, soil moisture based, and tensiometer based) conducted in the same year. The model was further evaluated using the data from cotton tillage and irrigation experiments conducted in an adjacent field during 2008-2010. The model calibration, validation, and evaluation results were satisfactory except under dry conditions (0% ET replacement and 33% ET replacement). Simulated maximum seed cotton yields under normal and dry weather conditions were achieved at 100% and 110% ET replacement, respectively. Percentage decrease in seed cotton yield was marginal (3.5% to 8.8%) when the amount of irrigation water applied was decreased from 100% to 66% ET replacement under normal rainfall conditions. However, under less than normal rainfall (drier) conditions, the percentage decrease in seed cotton yield was substantial (about 17.5%) when the irrigation strategy was switched from 100% to 70% ET replacement. The simulations demonstrate that adopting deficit irrigation practices under normal weather conditions can conserve water without adversely affecting seed cotton yields. However, under dry conditions, there is a risk of increased yield loss, and therefore producers should consider that risk when adopting deficit irrigation strategies.*

***Keywords.*** *Canopy height, Cotton, Crop growth model, Drought, Dry weather, Irrigation water savings, Leaf area index, Normal weather.*

In the agriculture industry across the globe, crop models are being extensively used by researchers and policy makers as important decision making tools for studying the impacts of climate change, management practices, and irrigation strategies on crop yields (Thorp et al., 2014a). Field experiments in these research areas are resource-intensive and challenging to implement. Under these circumstances, calibrated and validated crop models offer alternative solutions with comparable outcomes. Crop models differ in complexity, with some being very simple to use and requiring few input variables and others being complex and requiring many input variables. The Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 2012) crop models are complex, as they require many input parameters to provide in-depth assessments of crop growth and development and water and nutrient dynamics. DSSAT is a platform that encompasses 28 crop growth models covering fruit crops, vegetable crops, fiber crops, cereals, legumes, oil crops, and root crops. Each crop model simulates crop growth and development in response to weather conditions, soil properties, cultivar characteristics, and crop management data.

The Cropping System Model (CSM) CROPGRO-

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Cotton, distributed with DSSAT, can be used to study the impacts of climate change and management practices on crop growth, crop yields, and crop water use. The CSM-CROPGRO-Cotton model has so far been used in very few applications, mostly in the southeastern U.S., Africa, and Australia. Paz et al. (2012) used the CSM-CROPGRO-Cotton model to study the impacts of the El Niño/La Niña Southern Oscillation along with different planting dates on cotton yields at various spatial aggregations in 97 cotton-producing counties in Georgia. In another study (Garcia y Garcia et al., 2010), the CSM-CROPGRO-Cotton model was used to estimate the spatial and temporal distribution of water use efficiency of rainfed cotton across cotton-growing counties in Alabama, Florida, and Georgia. In another Georgia study, the CSM-CROPGRO-Cotton model was used in combination with spatial tools to assess the spatial distribution of monthly irrigation water use for cotton (Guerra et al., 2007). The CSM-CROPGRO-Cotton model was also used to study cotton growth and yield under the influence of southern root-knot nematode (*Meloidogyne incognita*) based on experiments conducted during 2007 in Tifton, Georgia (Ortiz et al., 2009).

A limited number of studies have calibrated the CSM-CROPGRO-Cotton model for their particular growing regions. For example, the CSM-CROPGRO-Cotton model was developed based on experiments conducted at various sites in Florida in an effort to study the effects of shading on specific leaf area, leaf area index, maximum leaf partitioning, carbon partitioning, and cotton production in a pecan alley cropping system (Zamora et al., 2009). Pathak et al. (2012) presented a detailed methodology and described a range of parameters that were adjusted for CSM-CROPGRO-Cotton calibration based on four experimental studies conducted in Florida and Georgia. Gérardeaux et al. (2013) developed a calibrated CSM-CROPGRO-Cotton model to study the effects of an ensemble of six regional climate projections on cotton yields in Cameroon. Their results showed an average increase in cotton yield by 1.3 kg $ha^{-1}$ $year^{-1}$ during the 2005-2050 period due to an increase in temperature and $CO_2$ concentration, and a decrease in precipitation. More recently, Thorp et al. (2014b) evaluated the CSM-CROPGRO-Cotton model using data from five cotton experiments conducted at Maricopa, Arizona. Their evaluation results indicated that the model demonstrated appropriate responses to water deficit, nitrogen deficit, planting density, and $CO_2$ enrichment. All of the above studies demonstrated the importance of calibrating the CSM-CROPGRO-Cotton model for particular cultivars and growing regions for successful model implementation.

Texas is the top cotton-producing state in the U.S., with a total production of 4.17 million bales of cotton in 2013, which is about 31.5% of the nation's cotton production (USDA-NASS, 2013, 2014). The Texas Rolling Plains (TRP) region in the north central Texas accounts for approximately 13% of the total cotton production in the state (DeLaune et al., 2012). Cotton production in the TRP region has experienced a noticeable decline in recent years due to reduced rainfall amounts and frequent occurrence of severe droughts. Since the TRP region receives inadequate rainfall to meet crop water demands in most years, farmers in this region rely on irrigation for meeting cotton water requirements. Since this region does not have adequate surface water resources, farmers use groundwater for irrigation. About 85% of the total water used for irrigation in the TRP region is pumped from underlying aquifers, and the remaining 15% is taken from surface water sources (county data provided by Mark Michon, Water Science and Conservation Division, Texas Water Development Board, personnel communication on February 15, 2012). Nielsen-Gammon (2011) predicted warmer summers in the future for this region, which will necessitate larger groundwater withdrawals to meet higher evapotranspiration needs. Studying the effects of various crop and irrigation management practices on cotton yields under current and future climate change scenarios and developing strategies for water conservation and climate change adaptation are therefore necessary for the TRP region, as cotton is one of the major revenue contributors to the local economy. The specific objectives of this study were to: (1) evaluate the CSM-CROPGRO-Cotton model for the TRP region using observed cotton growth and yield data over four growing seasons, and (2) identify appropriate deficit irrigation strategies that conserve water while obtaining optimum crop yields. The study emphasizes the establishment of a well-calibrated CSM-CROPGRO-Cotton model for the TRP region and description of the model calibration, validation, and evaluation approaches.

## Materials and Methods

### Study Area

The TRP region, encompassing 28 counties, lies in north central Texas and borders Oklahoma to the north (fig. 1). The Seymour aquifer is the major source of irrigation water for this region. The TRP region receives about 460 to 760 mm of annual rainfall, with maximum rainfall occurring from May to September. The 43-year (1971-2013)

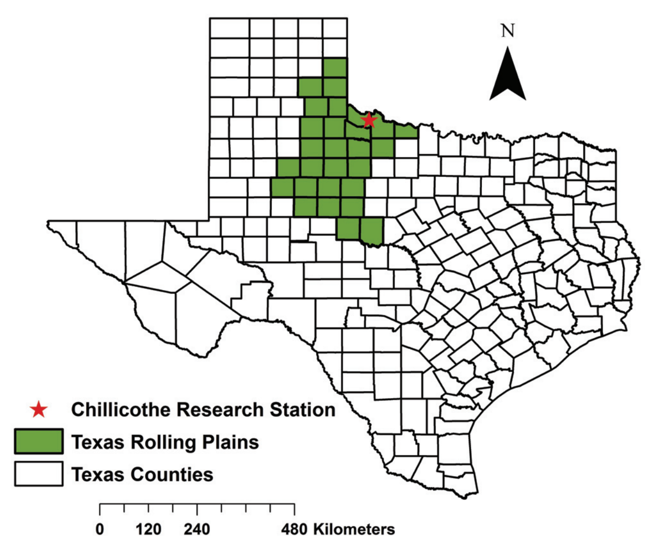


**Figure 1. Spatial extent of the Texas Rolling Plains region and location of the Chillicothe Research Station.**

average growing season (May to October) precipitation is about 420 mm (Porter et al., 2005; NCDC, 2014), and the mean temperature during this period is about 24°C. In general, precipitation decreases from east to west. The most common method of irrigation in the TRP is center-pivot sprinkler irrigation. About 85% of the groundwater pumped from the Seymour aquifer is used for irrigation. Major crops grown in the TRP are winter wheat, cotton, and sorghum, and the dominant soil type in the TRP region is Abilene clay loam.

### Field Experiments and Measured Data Sets

The observed data for evaluating the CSM-CROPGRO-Cotton model were obtained from cotton field experiments conducted at the Chillicothe Research Station (34.25° N, 99.51° W, 447 m above sea level) in Hardeman County, Texas (fig. 1) during the period from 2008 to 2012. While data from the 2012 irrigation scheduling experiment (Rajan et al., 2013) were used for model calibration and validation, the data from irrigation and tillage experiments conducted during 2008-2010 (DeLaune et al., 2012) were used for additional model evaluation. In 2012, four irrigation scheduling treatments (100% ET replacement, 75% ET replacement, tensiometer based irrigation scheduling, and soil moisture based irrigation scheduling) with three blocks were implemented in a randomized complete block design with each plot measuring 23 × 4.6 m. The 2008-2010 experiments were also conducted in a randomized block design with each plot measuring 45.7 × 8 m to study the combined effects of different tillage (conventional and conservation till) and irrigation regimes (0%, 33%, 66%, 100%, and 133% ET replacement) on cotton production. These experimental treatments were replicated three times.

In the 2012 irrigation scheduling experiment, soil moisture tension was measured using irrometers, and soil moisture was measured using CS 616 time domain reflectometry (TDR) probes. Data related to crop growth, crop development, and crop yields were collected during the study. The leaf area index (LAI), canopy height, phenology, and number of main stem nodes were also measured at various crop development stages. LAI was measured destructively using an LI-3100C leaf area meter (LICOR Biosciences, Lincoln, Neb.). Experimental plots were machine harvested, and the lint yields were estimated after ginning. More details about the 2008-2010 experiments can be found in DeLaune et al. (2012).

### Description of CSM-CROPGRO-Cotton Model

For this study, the CSM-CROPGRO-Cotton model was chosen due to its successful application for different cropping systems under different climatic conditions by various researchers across the globe. DSSAT is a platform that integrates the database management system (soil, climate, and management practices), crop models, and various application programs including sensitivity analysis and spatial analysis (Tsuji et al., 2002; Jones et al., 2003) by bringing together a diverse array of crop models in a single platform. The latest DSSAT, version 4.6 (Hoogenboom et al., 2012), is equipped with over 28 crop growth simulation models. Each crop growth model incorporated into DSSAT predicts crop growth, development and yield, soil water balance, evapotranspiration, soil moisture, and carbon and nitrogen processes over time based on weather, soils, crop management, and crop cultivar information.

The CSM-CROPGRO-Cotton model, which was developed from the CROPGRO-Soybean model, simulates crop growth and development on a daily time scale. It simulates different crop growth stages such as emergence, first leaf, first flower, first seed, first cracked boll, and 90% open boll based on the accumulation of heat units or photothermal time (Thorp et al., 2014a). The CSM-CROPGRO-Cotton model requires soil, management, environment, and cultivar parameters as inputs (Hunt et al., 2001).

The CSM-CROPGRO-Cotton model works by calculating various rate variables on a daily time step, integrating the model state variables over time, and finally updating the state variables (Jones et al., 2003). A warm-up period can be simulated in the model before planting for establishing the soil hydrological conditions. After planting, the model simulates carbon, nitrogen, and water dynamics as well as plant processes such as photosynthesis and respiration. The vegetative phase mostly depends on the supply of carbon and nitrogen (Jones et al., 2003). The carbon and nitrogen assimilation and partition are described in detail by Jones et al. (2003).

The soil water balance routine in DSSAT simulates daily soil water processes that affect the availability of soil water (Ritchie and Otter, 1985). Daily change in soil water availability is calculated based on the following equation:

$$\Delta S = P + I - ES - EP - R - D \tag{1}$$

where $\Delta S$ is change in storage, $P$ is precipitation, $I$ is irrigation, $ES$ is soil evaporation, $EP$ is transpiration, $R$ is runoff, and $D$ is drainage.

Soil moisture is distributed in several layers with depth increments specified by the user (Ritchie and Otter, 1985). Runoff is calculated using the modified Soil Conservation Service curve number technique (USDA-SCS, 1972) in which the wetness of the soil, which is calculated from the previous rainfall, replaces antecedent rainfall condition (Williams, 1991). This method, however, ignores rainfall intensity and assumes complete infiltration of applied irrigation water.

DSSAT estimates soil evaporation and plant transpiration separately. DSSAT uses the Priestly-Taylor (Priestly and Taylor, 1972) and FAO-56 methods (Allen et al., 1998) to estimate ET. The Priestly-Taylor method does not adequately account for advection (Ritchie, 1981). Since the TRP region experiences high wind speeds during the summer growing season, the FAO-56 method, which considers wind speed, was used for estimating evapotranspiration in this study. Potential plant transpiration was calculated as a function of potential evapotranspiration and light intercepted by the canopy. Detailed information about the methodologies and processes used in DSSAT can be found in the DSSAT documentation (Hoogenboom et al., 2010).

## Model Inputs

### *Weather Inputs*

Daily maximum temperature, minimum temperature, incoming solar radiation, precipitation, wind speed, and dew point temperature for the years 2008, 2009, 2010, and 2012 were obtained from the Texas High Plain Evapotranspiration Network (TXHPET) for the Chillicothe Research Station (Porter et al., 2005). Table 1 provides a monthly summary of the observed climate data for the growing period. The average soil temperature parameter (TAV) and soil temperature amplitude parameter (AMP) were estimated separately for each year. TAV and AMP were estimated as 25.7°C and 14.3°C, respectively, for the 2012 irrigation experiments. TAV and AMP were estimated to be respectively 24°C and 13.5°C for 2008, 26.1°C and 14.5°C for 2009, and 25°C and 13.5°C for 2010.

### *Management Inputs*

The crop, fertilizer, and irrigation management practices adopted during different years are outlined in table 2. The 'Deltapine 0912' cotton variety was planted at a seeding rate of 8 seeds per m of row and a row spacing of 1 m in the 2012 experiments. The pre-plant soil analysis showed higher levels of nitrogen residue in the soil, and hence no preplant nitrogen was applied. Nitrogen was knifed in as liquid fertilizer (28-0-0) during square formation at a rate of 35 kg ha$^{-1}$. Nitrate present in the irrigation water was not accounted for in this study. In the irrigation and tillage experiments conducted in 2008-2010, the 'Stoneville 4554 B2RF' cotton cultivar was planted with a seeding rate of 13.8 seeds per m of row. The nitrogen fertilizer was knifed on each side of the row three weeks after planting, prior to square formation (table 2). Seed cotton yields and lint yields were obtained from these experimental studies. The Deltapine 0912 and Stoneville 4554 cultivars are both early-maturing cotton varieties that have many similarities and are very widely used in the TRP region. The difference in maturity time of these two varieties is only three to five days (Dodds et al., 2011). In addition, the 2009 cotton variety trial data for central Texas indicated that these two vari-

**Table 1. Monthly summary of climate data for the growing season (May to October).[a]**

| Month | Average (1971-2013) RAIN (mm) | 2008 SRAD (MJ m$^{-2}$) | TMAX (°C) | TMIN (°C) | RAIN (mm) | DEW (°C) | WIND (km d$^{-1}$) | 2009 SRAD (MJ m$^{-2}$) | TMAX (°C) | TMIN (°C) | RAIN (mm) | DEW (°C) | WIND (km d$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| May | 79 | 851 | 38.1 | 16.8 | 79 | 11.9 | 287.6 | 692.7 | 36.1 | 7.0 | 59.1 | 13.3 | 256.0 |
| June | 95 | 852.5 | 40.2 | 15.4 | 109.5 | 17.0 | 355.9 | 768.4 | 40.4 | 17.7 | 67.7 | 13.0 | 269.7 |
| July | 45 | 827.3 | 41.6 | 18.3 | 39 | 17.1 | 268.2 | 853.0 | 42.6 | 17.6 | 54.6 | 16.9 | 260.8 |
| Aug. | 65 | 665.1 | 40.3 | 17.6 | 82.5 | 18.1 | 210.8 | 833.9 | 40.9 | 16.1 | 36.6 | 16.2 | 295.1 |
| Sept. | 70 | 596.4 | 35.2 | 10 | 48.2 | 14.6 | 164.8 | 567.9 | 38.1 | 8.3 | 75.6 | 14.5 | 227.7 |
| Oct. | 62 | 539.6 | 34 | -0.6 | 54.6 | 8.0 | 249.7 | 383.0 | 28.5 | 0.1 | 87.3 | 8.5 | 243.1 |
| Sum | 416 | 4332.1 | - | - | 412.4 | - | - | 4099.0 | - | - | 381.0 | - | - |
| Mean | | - | 32.8 | 9.5 | - | 12.3 | 219.3 | - | 32.4 | 8.9 | - | 12.5 | 221.8 |

| Month | 2010 SRAD (MJ m$^{-2}$) | TMAX (°C) | TMIN (°C) | RAIN (mm) | DEW (°C) | WIND (km d$^{-1}$) | 2012 SRAD (MJ m$^{-2}$) | TMAX (°C) | TMIN (°C) | RAIN (mm) | DEW (°C) | WIND (km d$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| May | 820.8 | 36.8 | 3.5 | 63.0 | 13.3 | 260.4 | 861.5 | 40.9 | 8.1 | 20.3 | 12.2 | 335.7 |
| June | 930.6 | 39.1 | 18.4 | 68.0 | 19.3 | 298.1 | 925.4 | 44.4 | 14.5 | 79.1 | 16.3 | 289.2 |
| July | 798.0 | 38.2 | 18.7 | 166.1 | 21.0 | 231.4 | 966.9 | 44.1 | 20.2 | 36.4 | 15.3 | 248.0 |
| Aug. | 900.0 | 40.2 | 13.4 | 34.1 | 17.8 | 218.4 | 714.1 | 44.2 | 16.1 | 80.2 | 14.6 | 214.5 |
| Sept. | 705.1 | 37.5 | 6.3 | 51.0 | 17.3 | 251.8 | 639.4 | 39.3 | 12.7 | 116.1 | 13.5 | 202.1 |
| Oct. | 594.8 | 32.6 | 2.4 | 38.1 | 6.8 | 195.4 | 551.1 | 35.3 | -3.1 | 8.7 | 7.0 | 233.0 |
| Sum | 4750.0 | - | - | 420.3 | - | - | 4658.4 | - | - | 340.8 | - | - |
| Mean | - | 32.0 | 8.9 | - | 13.6 | 207.3 | - | 35.4 | 9.8 | - | 11.3 | 217.5 |

[a] SRAD = incoming solar radiation, TMAX = maximum daily temperature, TMIN = minimum daily temperature, RAIN = precipitation, DEW = dew point temperature, and WIND = wind speed.

**Table 2. Details of management practices implemented in 2008-2010 and 2012 cotton field experiments.**

| Management Detail | 2012 | 2008 | 2009 | 2010 |
|---|---|---|---|---|
| Planting date | 23 May | 15 May | 21 May | 20 May |
| Irrigation system | Subsurface drip | Subsurface drip | Subsurface drip | Subsurface drip |
| Irrigation start date | 23 May[a], [b],[c],[d] | 22 May[e], [f], [g], [h] | 29 May[e], [f], [g], [h] | 29 May[e], [f], [g], [h] |
| Irrigation end date | 14 August[a], [b],[c],[d] | 3 September[e], [f], [g], [h] | 10 September[e], [f], [g]; 17 September[h] | 7 September[e], [f], [g], [h] |
| Irrigation amount (mm) | 416[a], 317[b], 344[c], 294[d] | 64[e], 132[f], 200[g], 265[h] | 134[e], 270[f], 380[g], 546[h] | 97[e], 191[f], 283[g], 377[h] |
| Type of fertilizer | Urea ammonium nitrate | Ammonium polyphosphate, urea ammonium nitrate | Ammonium polyphosphate, urea ammonium nitrate | Ammonium polyphosphate, urea ammonium nitrate |
| Amount of fertilizer | 35 kg N ha$^{-1}$ | 45 kg N ha$^{-1}$, 22 kg P ha$^{-1}$ | 67 kg N ha$^{-1}$, 34 kg P ha$^{-1}$ | 67 kg N ha$^{-1}$, 34 kg P ha$^{-1}$ |
| Tillage | Conventional | Conventional and conservation | Conventional and conservation | Conventional and conservation |
| Cultivar | Deltapine 0912 | Stoneville 4554 B2RF | Stoneville 4554 B2RF | Stoneville 4554 B2RF |

[a] = 100% ET replacement, [b] = 75% ET replacement, [c] = Tensiometer based scheduling, [d] = Soil moisture based scheduling, [e] = 33% ET replacement, [f] = 66% ET replacement, [g] = 100% ET replacement, and [h] = 133% ET replacement.

eties produced comparable cotton lint yields at Chillicothe under irrigated conditions (1234 kg $ha^{-1}$ for DP 0912 vs. 1241 kg $ha^{-1}$ for ST 4554) and at Dallas under dryland conditions (1549 kg $ha^{-1}$ for DP 0912 vs. 1386 kg $ha^{-1}$ for ST 4554) (Hague et al., 2009).

The CSM-CROPGRO-Cotton model does not have a provision to directly select tillage practices. Instead, the modeler can select a tillage implement used in an experiment and specify the tillage depth to represent conventional and conservation tillage practices. For conventional tillage, a bedder and row cultivator were used to a depth of 20 cm. For conservation tillage, a tandem disk was used to a depth of 10 cm. The irrigation efficiency of the subsurface drip irrigation system was assumed to be 95% in view of the negligible losses via evaporation.

### *Soil Inputs*

The dominant soil type at the study site is Abilene clay loam (fine mixed, super active, thermic parchic Argiustol), which has good drainage and moderately high saturated hydraulic conductivity (DeLaune et al., 2012). The soil profile was divided into six layers (0-5, 5-12, 12-30, 30-45, 45-60, and 60-160 cm) to account for heterogeneity in soil properties. Soil samples to a depth of 60 cm were collected before planting in 2012 and were analyzed for common soil properties. Regression equations were developed for each soil property based on the analyzed data. The regression equations were used to estimate the soil properties for the deeper layers (60-160 cm). Soil samples were analyzed for bulk density, pH, organic carbon, and percent silt and clay. The soil hydrological properties, including drained upper limit (DUL), lower limit (LL), saturated soil water content, and saturated hydraulic conductivity, were estimated using the ROSETTA pedotransfer tool (table 3) (Schaap et al., 2001). The neural network based ROSETTA tool uses five hierarchical pedotransfer functions to estimate soil hydrological properties based on the soil texture and bulk density. Soil bulk density was estimated based on soil texture within DSSAT. The root growth factor values were estimated using an exponential decay function in DSSAT. The runoff curve number (SLRO) was adjusted to 25.0 to simulate no runoff, as no runoff was observed due to dry weather conditions and the use of subsurface drip irrigation. A soil fertility factor (SLPF) of 1.0 was used in this study, as cotton is not expected to undergo nitrogen stress because soils in this region are generally rich in nitrogen due to natural and anthropogenic factors, such as the use of nitrogen fertilizers and irrigation with high nitrate groundwater (Chaudhuri et al., 2012). The same soil composition and hydrological properties were used for all the experiments.

## CSM-CROPGRO-COTTON MODEL CALIBRATION, VALIDATION, AND EVALUATION

The CSM-CROPGRO-Cotton model was calibrated using observed data from the 100% ET replacement treatment, which is expected to represent minimum or no stress conditions, implemented at Chillicothe in 2012 (Rajan et al., 2013). Data from the remaining three irrigation scheduling treatments, including 75% ET replacement and tensiometer and soil moisture based scheduling, were used for validation. The calibrated model was further evaluated using the seed cotton yield data from 30 treatments of a three-year (2008-2010) cotton irrigation and tillage study at Chillicothe (DeLaune et al., 2012).

Since the DSSAT cultivar database does not include Deltapine 0912 variety, we used the closest cultivar variety, GP 3774, that is already incorporated in the database for calibrating the CSM-CROPGRO-Cotton model for crop growth and development. A manual calibration approach was followed in which sensitive model parameters were adjusted and their effects on modeled processes were studied by visually comparing simulated versus observed crop growth and yield data and simultaneously assessing the model performance statistics. Four different statistical parameters, including percent error, root mean square error (RMSE) (Willmott, 1981), coefficient of determination ($R^2$) (Legates and McCabe, 1999), and coefficient of agreement (Willmott, 1981), were used to assess the performance of the CSM-CROPGRO-Cotton model. The model parameters were varied in such a way that the resultant RMSE was low (<0.5), the coefficient of agreement was high (>0.85), and the coefficient of determination ($R^2$) was high (>0.85). Finally, selected model parameter values were compared to the previously published studies (Pathak et al., 2007; Ortiz et al., 2009; Pathak et al., 2012; Thorp et al., 2014b). In this procedure, first the cultivar-specific parameters affecting crop phenology (table 4) were adjusted until the simulated crop phenology stages matched reasonably well with observed data. Secondly, the parameters affecting crop growth (table 4) were adjusted until a satisfactory match between simulated and observed LAI and canopy height were achieved. Finally, the parameters affecting crop yields (table 4) were adjusted until the predicted and observed seed cotton yields matched well. The cultivar-specific parameters that were adjusted during calibration are included in the cultivar (COGRO046.CUL), ecotype (COGRO046.ECO), and species (COGRO046.SPE) files. Model developers generally recommend not changing the parameters in the COGRO046.SPE file; however, in our

**Table 3. Soil composition and hydrological properties used for all simulations.[a]**

| Depth (cm) | SLCL (%) | SLSI (%) | SLOC (%) | SLHW | CEC (cmol $kg^{-1}$) | SLNI (%) | LL (cm $cm^{-1}$) | DUL (cm $cm^{-1}$) | SSAT (cm $cm^{-1}$) | SBDM (g $cm^{-3}$) | SSKS (cm $h^{-1}$) | SRGF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-5 | 26 | 40 | 1 | 7.3 | 20 | 0.1 | 0.103 | 0.319 | 0.440 | 1.32 | 0.67 | 0.950 |
| 5-15 | 26 | 40 | 1 | 7.3 | 20 | 0.1 | 0.103 | 0.319 | 0.440 | 1.32 | 0.67 | 0.950 |
| 15-30 | 28 | 32 | 0.67 | 7.7 | 20.3 | 0.07 | 0.109 | 0.301 | 0.428 | 1.40 | 0.46 | 0.850 |
| 30-45 | 34 | 27 | 0.64 | 7.6 | 21.4 | 0.07 | 0.126 | 0.311 | 0.439 | 1.41 | 0.45 | 0.775 |
| 45-60 | 32 | 34 | 0.48 | 7.9 | 23.5 | 0.05 | 0.118 | 0.314 | 0.439 | 1.39 | 0.44 | 0.700 |
| 60-160 | 32 | 34 | 0.31 | 7.9 | 23.5 | 0.04 | 0.117 | 0.311 | 0.434 | 1.41 | 0.39 | 0.320 |

[a] SLCL = clay content, SLSI = silt content, SLOC = organic carbon, SLHW = pH in water, CEC = cation exchange capacity, SLNI = total nitrogen concentration, LL = lower limit, DUL = drained upper limit, SSAT = saturation, SBDM = bulk density, SSKS = saturated hydraulic conductivity, and SRGF = soil root growth factor.

Table 4. CSM-CROPGRO-Cotton model parameters adjusted during the model calibration.

| Parameter | Description | Default Value | Testing Range | Calibrated Value |
|---|---|---|---|---|
| Crop phenology and development | | | | |
| PL-EM | Time between planting and emergence | 4 | 3 to 4 | 3 |
| FL-LF | Time between first flower and end of leaf expansion | 75 | 40 to 75 | 50 |
| FL-VS | Time from first flower to last leaf on main stem | 75 | 45 to 75 | 45 |
| Crop growth | | | | |
| LFMAX | Maximum leaf photosynthesis rate at 30°C, 350 ppm $CO_2$, and high light (mg $CO_2$ $m^{-2}$ $s^{-1}$) | 1.1 | 0.4 to 1.8 | 1.7 |
| RHGHT | Relative height of this ecotype in comparison to the standard height per node (YVSHT) defined in the species file | 0.95 | 0.55 to 0.95 | 0.6 |
| RWDTH | Relative width of this ecotype in comparison to the standard width per node (YVSWH) defined in the species file | 0.85 | 0.30 to 0.85 | 0.35 |
| TRIFL | Rate of appearance of leaves on the main stem | 0.2 | 0.18 to 0.30 | 0.3 |
| YHWTEM | Effect of temperature on the length of each internode | 0.01, 0.01, 0.33, 1.0, and 1.0 | - | 0.01, 0.02, 0.43, 0.85, and 0.85 |
| SLAVR | Specific leaf area of cultivar under standard growth conditions ($cm^2$ $g^{-1}$) | 170 | 130 to 200 | 130 |
| Crop yield | | | | |
| XFRT | Maximum fraction of daily growth that is partitioned to seed + shell | 0.55 | 0.3 to 0.9 | 0.75 |
| SFDUR | Seed filling duration for pod cohort at standard growth conditions | 24 | 20 to 35 | 30 |
| LNGSH | Time required for growth of individual shells | 8 | 7 to 15 | 14 |

study, one of the cultivar parameters in this file, XVSHT (number of average observed nodes), was adjusted based on the observations made at the study site, and another parameter, YHWTEM (effect of temperature on the length of each node), was adjusted in order to obtain a better match between the observed and simulated canopy heights. The cotton parameters that were adjusted during the model calibration are listed in table 4. The testing ranges of the cultivar parameters in table 4 were selected based on published studies (Ortiz et al., 2009; Pathak et al., 2012; Thorp et al., 2014b) and according to expert opinions.

### Determination of Appropriate Deficit Irrigation Strategies for the Texas Rolling Plains

The calibrated model was used to determine appropriate deficit irrigation strategies for the TRP region that conserve water under different climatic conditions. For the years 2008 to 2010, deficit irrigation strategies with 0%, 33%, 66%, 100%, and 133% ET replacement were implemented in the calibrated model to compare the simulated results with observed data for these treatments (DeLaune et al., 2012). For the year 2012, deficit irrigation strategies with 0% to 130% ET replacement with an increment of 10% were simulated and analyzed.

## Results and Discussion

### Calibration

With default parameters, the model predicted plant emergence as 8 days after planting (DAP) (results not shown), so the phenology parameter PL-EM in the cultivar file was adjusted to 3 photothermal days to simulate plant emergence as 5 DAP, as measured during the experiment (Modala, 2014). Parameter FL-LF in the cultivar file and parameter FL-VS in the ecotype file were then adjusted to simulate the end of leaf expansion stage and end of node expansion stage, respectively, according to field observations. After these adjustments, simulated dates of anthesis, first flower, 50% boll opening, and physiological maturity fell within the range of observed dates in the TRP region (table 5).

With default cultivar characteristics, the model underestimated LAI across all growth stages and overestimated canopy height by 45% (results not shown). The maximum leaf photosynthesis rate (LFMAX) (table 4) was therefore adjusted to 1.7 after making sure that the model was not simulating any water and nitrogen stresses. A value of 130 was obtained for the specific leaf area (SLAVR) of the cultivar, which is the ratio of leaf area to leaf weight, by averaging the observed leaf area and leaf weight values. The parameters TRIFL (rate of appearance of leaves on the main stem) and SLAVR were adjusted (table 4) to improve the match between simulated versus observed LAI (fig. 2a). After adjusting the above-mentioned parameters, the model was able to simulate the LAI trend satisfactorily; however, the model underestimated LAI after entering the reproductive phase (fig. 2a, table 6). During the reproductive phase, the model directed most of the available carbon toward the development of reproductive parts, and thus less carbon was available for the development of vegetative parts (leaf and stem), resulting in the underestimation of LAI. The CSM-CROPGRO-Cotton model calibration for canopy height prediction required changing parameters in the species file. The number of nodes on the main stem (XVSHT) was adjusted based on observed data at various crop growth stages (table 7).

Since the uncalibrated model underpredicted the canopy height during the early growing season and overpredicted

Table 5. Comparison of observed and simulated dates of crop phenological stages during model calibration (DAP = days after planting).

| Crop Phenological Stage | Observed (DAP) | Simulated (DAP) |
|---|---|---|
| Emergence | 5 | 5 |
| Onset of anthesis | 46 | 49 |
| Planting to harvest[a] | 130-160 | 154 |

[a] Source: www.cotton.org/tech/ace/growth-and-development.cfm.

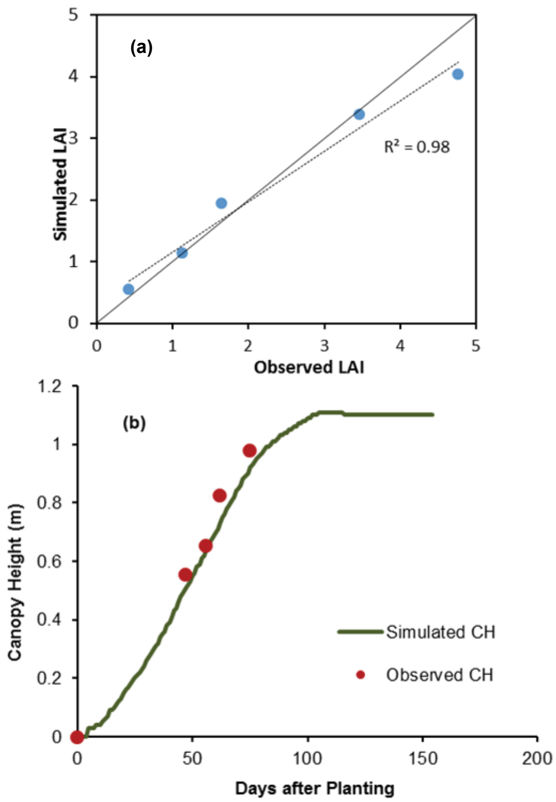


**Figure 2. Comparison of simulated and observed (a) LAI and (b) canopy height of cotton during model calibration.**

the canopy height during the late growing season, the species file parameter YHWTEM, which defines the effect of temperature on the length of each internode, was increased during the initial vegetative phase and decreased during the beginning of the anthesis phase (table 4). The parameters RHGHT and RWDTH were also adjusted to attain a reasonable canopy height simulation (fig. 2b, table 6). Finally, the cultivar parameters XFRT, SFDUR, LNGSH, and TRIFL were adjusted during model calibration to attain a better match between observed and simulated seed cotton yields (table 4). The calibrated model simulated a seed cotton yield of 4831 kg ha$^{-1}$, as compared to an observed seed cotton yield of 4781 kg ha$^{-1}$, with an error of 1%.

**Table 6. Model performance in LAI and canopy height prediction during model calibration.**

| Variable | $R^2$ | Root Mean Square Error | Coefficient of Agreement |
|---|---|---|---|
| LAI | 0.98 | 0.35 | 0.98 |
| Canopy height | 0.97 | 0.06 | 0.96 |

**Table 7. Number of nodes observed at various development stages.**

| Plant Development Stage | Average No. of Observed Nodes |
|---|---|
| Planting | 0 |
| Emergence | 1 |
| V1 phase | 5 |
| End of juvenile stage | 10 |
| Flower induction | 10 |
| First flower | 16 |
| First peg | 18 |
| First pod | 20 |
| First seed | 24 |
| Last seed | 25 |

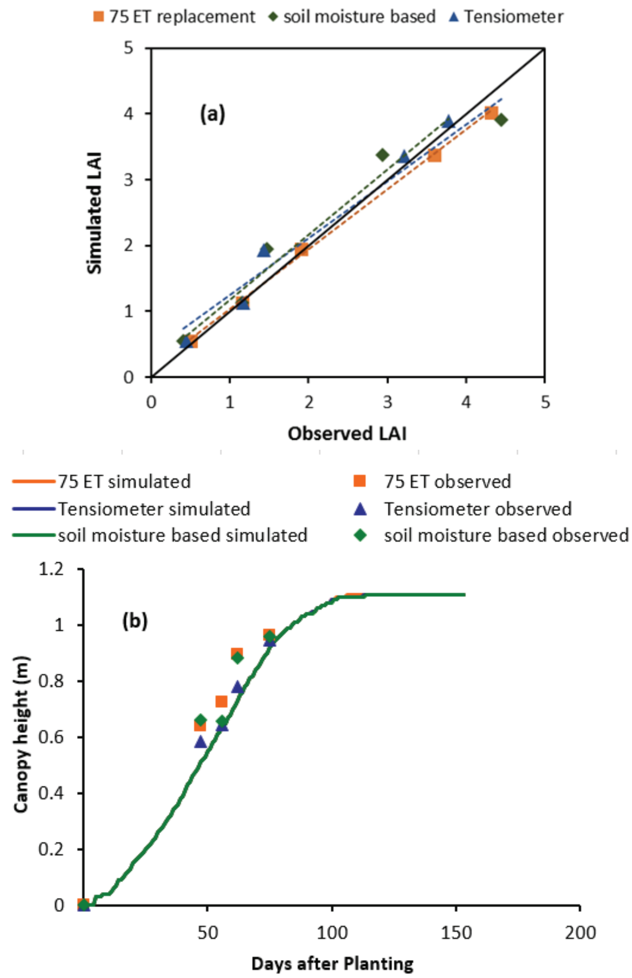


**Figure 3. Comparison of simulated and observed (a) LAI and (b) canopy height of cotton during model validation.**

## Validation

The calibrated CSM-CROPGRO-Cotton model was validated using the data from three other irrigation scheduling treatments implemented in 2012. These three treatments had the same experimental setup as the 100% ET replacement treatment except for the method of estimating daily irrigation amounts. The total irrigation amounts applied during the growing season were 329 mm for the 75% ET treatment, 344 mm for the tensiometer based experiment, and 295 mm for the soil moisture based scheduling method. The model performance during the validation was satisfactory, as indicated by the agreement between the observed and simulated LAI ($R^2 > 0.85$) (fig. 3a, table 8) and canopy height ($R^2 = 0.83$ to 0.97) (fig. 3b, table 8). Although the model simulated LAI reasonably well when compared to the calibration results, it slightly underpredicted canopy height among all treatments. The simulated crop yields for these three treatments also matched satisfactorily, as indicated by the low percent error, which fell within an acceptable range of -9.2% to -1.4% (table 9).

## Model Evaluation

The CSM-CROPGRO-Cotton model was further evaluated using the data from a three-year study on cotton irrigation and tillage management conducted on an adjacent sub-

Table 8. Model performance statistics for LAI and canopy height prediction during model validation.

| Irrigation Scheduling Treatment | $R^2$ | | Root Mean Square Error | | Coefficient of Agreement | |
|---|---|---|---|---|---|---|
| | LAI | Height | LAI | Height | LAI | Height |
| 75% ET replacement | 0.99 | 0.92 | 0.16 | 0.12 | 1.00 | 0.85 |
| Tensiometer based | 0.98 | 0.97 | 0.25 | 0.05 | 0.99 | 0.97 |
| Soil moisture based | 0.94 | 0.83 | 0.38 | 0.11 | 0.98 | 0.86 |

Table 9. Comparison of observed and simulated seed cotton yields during model validation.

| Irrigation Scheduling Treatment | Observed Yield (kg ha$^{-1}$) | Simulated Yield (kg ha$^{-1}$) | Percent Error (%) |
|---|---|---|---|
| 75% ET replacement | 4783 | 4402 | -7.9 |
| Tensiometer based | 4613 | 4188 | -9.2 |
| Soil moisture based | 4279 | 4217 | -1.4 |

surface drip irrigated field from 2008 to 2010 (DeLaune et al., 2012). The seed cotton yields simulated by the CSM-CROPGRO-Cotton model for all irrigated treatments were in an error range of -24% to 13%, except for the 0% (rainfed) and 33% ET replacement treatments (table 10). For the dry treatments (0% and 33% ET replacements), the model mostly overestimated cotton seed yield for conservation tillage treatments, except for the 2008 rainfed and 2010 33% ET replacement treatments, and underestimated cotton seed yield for the conventional tillage treatments, except for the 2008 33% ET replacement and 2010 rainfed treatments (table 10). Poor performance of DSSAT CSMs under water-stressed conditions was also reported in previous studies (Nouna et al., 2000; Ines et al., 2001; Thorp et al., 2014b). For example, Nouna et al. (2000) reported about 15% and 23% underprediction of maize yields under moderate and severe soil water deficit conditions, respectively, using the DSSAT-CERES-Maize model. The ET routines in DSSAT CSMs have been found to be unsatisfactory for ET simulations in water-limited environments (Ines et al., 2001; DeJonge et al., 2012; Thorp et al., 2014b), and ongoing research aims to correct those deficiencies by making the ET algorithms more in line with standardized ET procedures. Recently, while evaluating the CSM-CROPGRO-Cotton model for arid Arizona conditions, Thorp et al. (2014b) modified the ET algorithms based on the ASCE standardized ET equation to overcome the problem of underprediction of ET. In future studies, we aim to use the modified ET algorithms in DSSAT CSMs to overcome these deficiencies in the model.

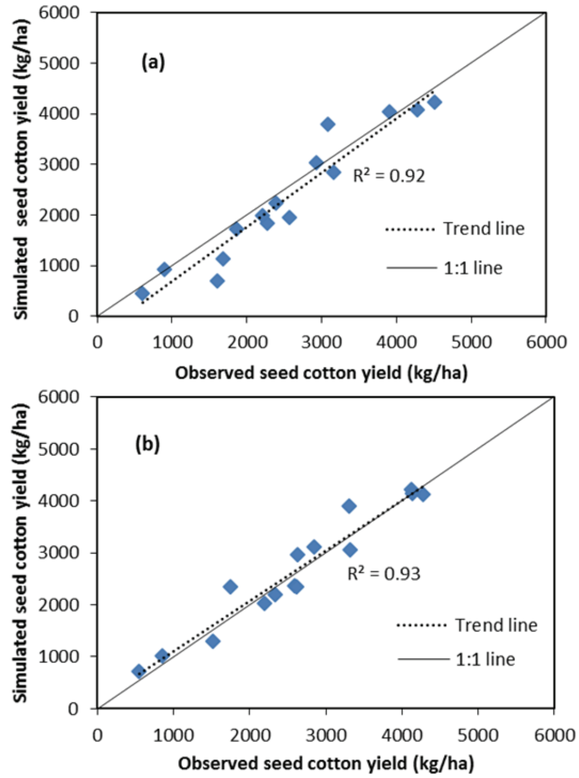


Figure 4. Comparison of simulated and observed crop yields from various irrigation treatments under (a) conventional tillage (b) conservation tillage during model evaluation.

The model predictions for conservation tillage were slightly better than those for conventional tillage (table 10). Although the model performance under extremely dry conditions was poor due to the reasons explained above, overall the model predicted seed cotton yield reasonably well ($R^2 \approx 0.90$) for 15 conventional (fig. 4a) and 15 conservation tillage (fig. 4b) treatments during the 2008-2010 cropping seasons.

Table 10. Observed and simulated seed cotton yields for various 2008-2010 treatments during model evaluation.

| Year | Treatments (Percent ET Replacement) | Conventional Tillage Observed Yield (kg ha$^{-1}$) | Conventional Tillage Simulated Yield (kg ha$^{-1}$) | Conventional Tillage Percent Error | Conservation Tillage Observed Yield (kg ha$^{-1}$) | Conservation Tillage Simulated Yield (kg ha$^{-1}$) | Conservation Tillage Percent Error |
|---|---|---|---|---|---|---|---|
| 2008 | 0 | 1603 | 691 | -56.9 | 2189 | 2028 | -7.3 |
| | 33 | 3082 | 3788 | 22.9 | 3310 | 3893 | 17.6 |
| | 66 | 3912 | 4044 | 3.4 | 4284 | 4130 | -3.6 |
| | 100 | 4279 | 4080 | -4.6 | 4123 | 4224 | 2.4 |
| | 133 | 4507 | 4231 | -6.1 | 4139 | 4153 | 0.3 |
| 2009 | 0 | 607 | 455 | -25 | 548 | 723 | 31.9 |
| | 33 | 1859 | 1733 | -6.8 | 1752 | 2348 | 34.0 |
| | 66 | 2391 | 2239 | -6.4 | 2624 | 2971 | 13.2 |
| | 100 | 3156 | 2838 | -10.1 | 3319 | 3053 | -8.0 |
| | 133 | 2936 | 3035 | 3.4 | 2845 | 3119 | 9.6 |
| 2010 | 0 | 901 | 934 | 3.7 | 854 | 1010 | 18.3 |
| | 33 | 1678 | 1137 | -32.2 | 1515 | 1307 | -13.7 |
| | 66 | 2269 | 1845 | -18.7 | 2329 | 2201 | -5.5 |
| | 100 | 2215 | 1998 | -9.8 | 2593 | 2362 | -8.9 |
| | 133 | 2573 | 1959 | -23.9 | 2616 | 2351 | -10.1 |

Table 11. Comparison of simulated and observed/reported irrigation water use efficiency (IWUE) at Chillicothe under conservation tillage (CST) and conventional tillage (CVT) practices.

| Percent ET Replacement | DSSAT-Simulated Average (2008-2010) IWUE (kg m$^{-3}$) CST Treatment | CVT Treatment | CST and CVT Combined | Observed/Reported Average (2008-2010) IWUE (DeLaune et al., 2012), CST and CVT Combined (kg m$^{-3}$) |
|---|---|---|---|---|
| 33 | 1.34 | 1.20 | 1.27 | 1.25 |
| 66 | 0.96 | 0.85 | 0.90 | 1.01 |
| 100 | 0.70 | 0.67 | 0.69 | 0.80 |
| 133 | 0.51 | 0.51 | 0.51 | 0.58 |

The irrigation water use efficiency (IWUE), a ratio of the difference between irrigated seed cotton yield and dryland seed cotton yield divided by the total amount of irrigation water applied (Howell, 2003; DeLaune et al., 2012), was also estimated for these modeling exercises and compared with the observed efficiencies (table 11). The IWUE values calculated from the simulated seed cotton yields were comparable with the observed IWUE values. The simulated IWUE decreased with increased irrigation amounts, a trend that was also observed in other field studies (Bordovsky et al., 1992; DeLaune et al., 2012). When compared to conventional tillage, the simulated IWUE under conservation tillage was higher by 11.7%, 12.9%, and 4.5% for the 33%, 66%, and 100% ET replacement treatments, respectively. However, the simulated IWUE for the 133% ET replacement treatment was the same under both conservation and conventional tillage practices. Higher IWUE with conservation tillage under deficit irrigation indicates higher soil moisture availability due to increased infiltration and reduced surface runoff. These results indicate that switching from conventional tillage to conservational tillage could potentially improve or at least maintain cotton yields under different irrigation strategies.

## Model Application

The calibrated model was used to determine suitable deficit irrigation strategies for the TRP region for the weather conditions during the years 2008-2010 and 2012. The weather conditions experienced in the TRP region during the 2008-2010 period were characterized as "normal" based on the 43-year (1971-2013) average growing season (May to October) rainfall of 416 mm, in comparison to 412.4, 381.0, and 420.3 mm of rainfall received during the growing seasons of 2008, 2009, and 2010, respectively (table 1). In contrast, the weather conditions in the 2012 growing season were substantially "drier" with 21% less rainfall (340.8 mm) when compared to the 43-year average rainfall (table 1) and an increase in mean temperature of 1.85°C when compared to 2008-2010. Simulated average (2008-2010) seed cotton yields under different ET replacement strategies (0% to 133% ET replacement) for both conventional and conservation tillage followed a trend similar to that observed by DeLaune et al. (2012) in their field experiments (fig. 5). The maximum simulated yields were obtained for 133% ET replacement with conventional tillage and for 100% ET replacement with conservation tillage. When the irrigation strategy was changed from 100% ET replacement to 133% ET replacement, the simulated seed cotton yield increased by 3.5% with conventional tillage and slightly decreased by 0.2% with conservation tillage (fig. 5). When the irrigation strategy was changed

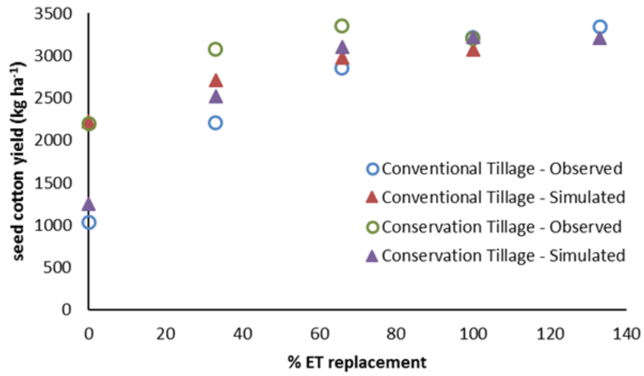


Figure 5. Average (2008-2010) seed cotton yields under various deficit irrigation strategies.

from 100% ET replacement to 66% ET replacement (a 31% decrease in the amount of irrigation water applied), the simulated seed cotton yield decreased by 8.8% and 3.5% with conventional and conservation tillage, respectively.

In 2012, the CSM-CROPGRO-Cotton model simulated the highest seed cotton yield of 5217 kg ha$^{-1}$ with 110% ET replacement, and the simulated yield for 100% ET replacement was 4831 kg ha$^{-1}$. The crop yields started declining above 120% ET replacement (fig. 6). Therefore, to achieve a 6% increase in seed cotton yield, about 20% of additional irrigation water (100% ET replacement to 120% ET replacement) was needed. Similarly, to achieve a 21% increase in seed cotton yield from 70% ET replacement to 100% ET replacement, about 43% of additional irrigation water was needed (fig. 6). The water productivity was therefore higher between 70% and 100% ET replacement when compared to the treatments with greater than 100% ET replacement. The simulated trends obtained in this study are comparable to the findings of Bronson et al. (2001) for the nearby Southern High Plains region, who reported that the optimum cotton yields under surface drip

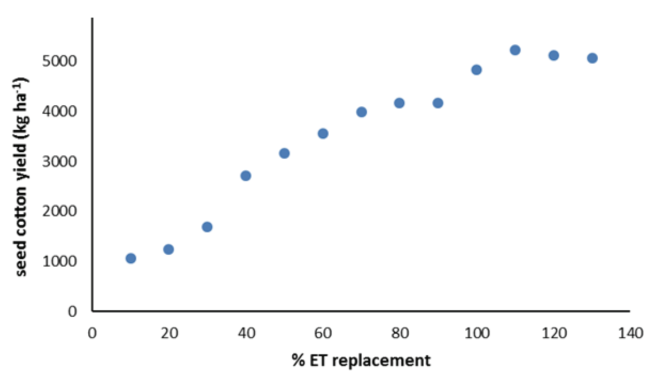


Figure 6. Simulated seed cotton yields under various deficit irrigation strategies during 2012.

irrigation could be achieved by adopting deficit irrigation strategies with 71% to 97% ET replacement. In another study in southwest Texas, Falkenberg et al. (2007) reported that deficit irrigation down to 75% of maximum ET had no impact on cotton lint yield. Basal et al. (2009) also reported that deficit irrigation with 75% ET replacement decreased the seed cotton yield by only 8% as compared to full irrigation.

From the above two simulation experiments, it can be noted that the relationship between seed cotton yields at various percentages of ET replacement was very different among the years studied (figs. 5 and 6), mainly because of the differences in weather conditions during the growing seasons. The results indicated that the application of any additional irrigation water above 100% ET replacement would not be advantageous under both normal and drier weather conditions. A substantial savings in irrigation water can be achieved without adversely impacting cotton yields in a normal year by adopting deficit (<100% ET replacement) irrigation strategies. However, in a drier (less than normal rainfall) year, adoption of deficit irrigation strategies could substantially affect cotton yields, and hence 100% ET replacement would be necessary to maintain crop yields (fig. 6). From figures 5 and 6, it can be inferred that some of the allowed deficit will be removed at random times due to rainfall, lessening the impact of a deficit irrigation strategy on yield. However, there is a risk of increased yield loss in years when no rainfall occurs, and producers should consider that risks when adopting deficit irrigation strategies. Furthermore, the suggested deficit irrigation strategies are intended for the Deltapine 0912 and similar cotton cultivars for the TRP region. When these calibrated parameters are used for other cotton cultivars with significantly different growth characteristics in this region, modelers should exercise caution and make necessary adjustments to the cultivar parameters, and then use the re-evaluated model to determine appropriate deficit irrigation strategies.

## SUMMARY AND CONCLUSIONS

A well-calibrated CSM-CROPGRO-Cotton model was successfully established for Chillicothe in the TRP region after its extensive testing on two different experiments that were conducted during 2008 to 2012. The model predicted crop phenology stages, LAI ($R^2$ = 0.98), canopy height ($R^2$ = 0.97), and crop yield (% error= 1.0) adequately for the 100% ET replacement treatment during model calibration. The model responded well to changes in irrigation amounts during validation, as indicated by a close match between the simulated and observed LAI, canopy height, and crop yields on three other (75% ET replacement, tensiometer based, and soil moisture based) irrigation scheduling treatments. The model was further evaluated on a three-year (2008-2010) tillage and irrigation experiment, and the simulated seed cotton yields were within the acceptable error range (-24% to 13%), except for dry treatments (rainfed and 33% ET replacement). The model's ET routines have been found to be unsatisfactory for ET simulations in water-limited environments, and hence the current version of this model has a limitation in accurately predicting seed cotton yield under mild to extremely dry conditions. Except for the extremely dry conditions, the evaluated CSM-CROPGRO-Cotton model demonstrated the potential to simulate cotton growth and development in the TRP region and predicted seed cotton yields in response to different management practices and climatic conditions reasonably well.

The calibrated model was used to evaluate deficit irrigation strategies for this region. It was found that significant water savings could be achieved without severely affecting crop yields by adopting deficit irrigation strategies under normal weather conditions, such as those during 2008 to 2010. However, during drier conditions, such as in 2012, practicing deficit irrigation can significantly reduce crop yields. Even in a dry year, deficit irrigation will probably be an optimum strategy, especially if irrigation water is applied at critical growth stages. In future studies, the calibrated CSM-CROPGRO-Cotton model will be used to evaluate the effects of future climate change on cotton yields in the TRP region and to develop optimal irrigation and crop management practices that can mitigate (or adapt to) the effects of climate change.

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## REFERENCES

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome, Italy: United Nations FAO.

Basal, H., Dagdelen, N., Unay, A., & Yilmaz, E. (2009). Effects of deficit drip irrigation ratios on cotton (*Gossypium hirsutum* L.) yield and fiber quality. *J. Agron. Crop Sci., 195*(1), 19-29. http://dx.doi.org/10.1111/j.1439-037X.2008.00340.x.

Bordovsky, J. P., Lyle, W. M., Lascono, R. J., & Upchurch, D. R. (1992). Cotton irrigation management with LEPA systems. *Trans. ASAE, 35*(3), 879-884. doi.org/10.13031/2013.28673.

Bronson, K., Onken, A., Keeling, J., Booker, J., & Torbert, H. (2001). Nitrogen response in cotton as affected by tillage system and irrigation level. *SSSA J., 65*(4), 1153-1163. http://dx.doi.org/10.2136/sssaj2001.6541153x.

Chaudhuri, S., Ale, S., DeLaune, P. B., & Rajan, N. (2012). Spatio-temporal variability of groundwater nitrate concentration in Texas: 1960 to 2010. *J. Environ. Qual., 41*(6), 1806-1817. http://dx.doi.org/10.2134/jeq2012.0022.

DeJonge, K. C., Ascough, J. C., Andales, A. A., Hansen, N. C., Garcia, L. A., & Arabi, M. (2012). Improving evapotranspiration simulations in the CERES-Maize model under limited irrigation. *Agric. Water Mgmt., 115*, 92-103. http://dx.doi.org/10.1016/j.agwat.2012.08.013.

DeLaune, P., Sij, J., Park, S., & Krutz, L. (2012). Cotton production as affected by irrigation level and transitioning tillage systems. *Agron. J., 104*(4), 991-995. http://dx.doi.org/10.2134/agronj2011.0420.

Dodds, D. M., Catchot, A., & Gore, J. (2011). 2011 Cotton maturity guide. Mississippi State, Miss.: Mississippi State University Extension Service. Retrieved from http://msucares.com/pubs/publications/p2697.pdf.

Falkenberg, N. R., Piccinni, G., Cothren, J. T., Leskovar, D. I., & Rush, C. M. (2007). Remote sensing of biotic and abiotic stress for irrigation management of cotton. *Agric. Water Mgmt., 87*(1), 23-31. http://dx.doi.org/10.1016/j.agwat.2006.05.021.

Garcia y Garcia, A., Persson, T., Paz, J. O., Fraisse, C., & Hoogenboom, G. (2010). ENSO-based climate variability affects water use efficiency of rainfed cotton grown in the southeastern USA. *Agric., Ecosyst. Environ., 139*(4), 629-635. http://dx.doi.org/10.1016/j.agee.2010.10.009.

Gérardeaux, E., Sultan, B., Palaï, O., Guiziou, C., Oettli, P., & Naudin, K. (2013). Positive effect of climate change on cotton in 2050 by $CO_2$ enrichment and conservation agriculture in Cameroon. *Agron. Sustain. Devel., 33*(3), 485-495. http://dx.doi.org/10.1007/s13593-012-0119-4.

Guerra, L., Garcia y Garcia, A., Hook, J., Harrison, K., Thomas, D., Stooksbury, D., & Hoogenboom, G. (2007). Irrigation water use estimates based on crop simulation models and kriging. *Agric. Water Mgmt., 89*(3), 199-207. http://dx.doi.org/10.1016/j.agwat.2007.01.010.

Hague, S., Smith, W., Deno, D., Brown, N., Jones, D., Jones, C., & Schaefer, K. (2009). Cotton cultivar tests for 2009 in central and south Texas. College Station, Tex.: Texas A&M University. Retrieved from http://varietytesting.tamu.edu/cotton/files/2009/09%20Cotton%20Variety%20Trials%20for%20Central%20and%20South%20Texas%20final.pdf.

Hoogenboom, G., Jones, J. W., Porter, C. H., Wilkens, P. W., Boote, K. J., Hunt, L. A., & Tsuji, G. Y. (Eds.). (2010). *Decision Support System for Agrotechnology Transfer Version 4.5: Volume 1. Overview*. Honolulu, Hawaii: University of Hawaii.

Hoogenboom, G., Jones, J. W., Wilkens, P., Porter, C., Boote, K. J., Hunt, L. A., Singh, U., Lizaso, J. L., White, J. W., Uryasev, O., Royce, F. S., Ogoshi, R., Gijsman, A. J., Tsuji, G. Y., & Koo, J. (2012). Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5. Honolulu, Hawaii: University of Hawaii.

Howell, T. A. (2003). Irrigation efficiency. In B. A. Stewart, & T. A. Howell (Eds.), *Encyclopedia of Water Science*, pp. 467-472. New York, N.Y.: Marcel Dekker.

Hunt, L. A., White, J. W., & Hoogenboom, G. (2001). Agronomic data: Advances in documentation and protocols for exchange and use. *Agric. Systems 70*(2), 477-492. http://dx.doi.org/10.1016/S0308-521X(01)00056-7.

Ines, A. V. M., Droogers, P., Makin, I. W., & Gupta, A. D. (2001). Crop growth and soil water balance modeling to explore water management options. Working Paper 22. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L., & Ritchie, J. T. (2003). The DSSAT cropping system model. *European J. Agron., 18*(3), 235-265. http://dx.doi.org/10.1016/S1161-0301(02)00107-7.

Legates, D. R., & McCabe, G. J. (1999). Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation. *Water Resources Res., 35*(1), 233-241. http://dx.doi.org/10.1029/1998WR900018.

Modala, N. R. (2014). Assessing the impacts of climate change on cotton production in the Texas High Plains and Rolling Plains. PhD diss. College Station, Tex.: Texas A&M University, Department of Biological and Agricultural Engineering.

NCDC. (2014). Weather data. Asheville, N.C.: National Climatic Data Center. Retrieved from www.ncdc.noaa.gov/.

Nielsen-Gammon, J. (2011). The changing climate of Texas. In J. Schmandt, G. D. North, and J. Clarkson (Eds.), *The Impact of Global Warming on Texas*, pp. 39-68. Austin, Tex.: University of Texas Press.

Nouna, B. B., Katerji, N., & Mastrorilli, M. (2000). Using the CERES-Maize model in a semi-arid Mediterranean environment. Evaluation of model performance. *European J. Agron., 13*(4), 309-322. http://dx.doi.org/10.1016/S1161-0301(00)00063-0.

Ortiz, B., Hoogenboom, G., Vellidis, G., Boote, K., Davis, R., & Perry, C. (2009). Adapting the CROPGRO-Cotton model to simulate cotton biomass and yield under southern root-knot nematode parasitism. *Trans. ASABE, 52*(6), 2129-2140. http://dx.doi.org/10.13031/2013.29201.

Pathak, T., Fraisse, C., Jones, J., Messina, C., & Hoogenboom, G. (2007). Use of global sensitivity analysis for CROPGRO cotton model development. *Trans. ASABE, 50*(6), 2295-2302. http://dx.doi.org/10.13031/2013.24082.

Pathak, T. B., Jones, J. W., Fraisse, C. W., Wright, D., & Hoogenboom, G. (2012). Uncertainty analysis and parameter estimation for the CSM-CROPGRO-Cotton model. *Agron. J., 104*(5), 1363-1373. http://dx.doi.org/10.2134/agronj2011.0349.

Paz, J. O., Woli, P., Garcia y Garcia, A., & Hoogenboom, G. (2012). Cotton yields as influenced by ENSO at different planting dates and spatial aggregation levels. *Agric. Syst., 111*, 45-52. http://dx.doi.org/10.1016/j.agsy.2012.05.004.

Porter, D. T., Marek, T., Howell, T., & New, L. (2005). The Texas High Plains Evapotranspiration Network (TXHPET) User Manual. AREC 05-37. Amarillo, Tex.: Texas AgriLife Research and Extension Center.

Priestley, C., & Taylor, R. (1972). On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Re., 100*(2), 81-92. http://dx.doi.org/10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2.

Rajan, N., Ale, S., & DeLaune, P. B. (2013). Demonstrating tools for improving on-farm irrigation efficiency. Austin, Tex.: Texas Water Development Board. Retrieved from https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1103581253_irrigationefficiency.pdf

Ritchie, J. T. (1981). Water dynamics in the soil-plant-atmosphere system. *Plant Soil, 58*(1-3), 81-96. http://dx.doi.org/10.1007/978-94-015-0861-2_4.

Ritchie, J. T., & Otter, S. (1985). Description and performance of CERES-Wheat: A user-oriented wheat yield model. Washington, D.C.: USDA Agricultural Research Service.

Schaap, M. G., Leij, F. J., & van Genuchten, M. T. (2001). Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *J. Hydrol., 251*(3), 163-176. http://dx.doi.org/10.1016/S0022-1694(01)00466-8.

Thorp, K., Ale, S., Bange, M., Barnes, E., Hoogenboom, G., Lascano, R., McCarthy, A. C., Nair, S., Paz, J. O., Rajan, N., Reddy, K. R., Wall, G. W., & White, J. W. (2014a). Development and application of process-based simulation models for cotton production: A review of past, present, and future directions. *J. Cotton Sci., 18*(1), 10-47.

Thorp, K., Barnes, E. M., Hunsaker, D. J., Kimball, B. A., White, J. W., Nazareth, V. J., & Hoogenboom, G. H. (2014b). Evaluation of CSM-CROPGRO-Cotton for simulating effects of management and climate change on cotton growth and evapotranspiration in an arid environment. *Trans. ASABE, 57*(6), 1627-1642. http://dx.doi.org/10.13031/trans.57.10612.

Tsuji, G. Y., du Toit, A., Jintrawet, A., Jones, J., Bowen, W. T., Ogoshi, R. M., & Uehara, G. (2002). Benefits of models in research and decision support: The IBSNAT experience. In L. R. Ahuja, L. Ma, and T. A. Howell (Eds.), *Agricultural System*

*Models Field Research and Technology Transfer*, 71-89. Boca Raton, Fla.: CRC Press. http://dx.doi.org/10.1201/9781420032413.ch5.

USDA-NASS. (2013). Winter wheat production up 7 percent from 2014, orange production down 4 from April forecast. Washington, D.C.: USDA National Agricultural Statistics Service. Retrieved from www.usda.gov/nass/PUBS/TODAYRPT/crop0515.pdf.

USDA-NASS. (2014). Texas cotton production. PR-123-14. Washington, D.C.: USDA National Agricultural Statistics Service. Retrieved from www.nass.usda.gov/Statistics_by_State/Texas/Publications/Current_News_Release/2014_Rls/pr12314.pdf.

USDA-SCS. (1972). *National Engineering Handbook, Section 4: Hydrology*. Washington, D.C.: USDA Soil Conservation Service.

Williams, J. (1991). Runoff and water erosion. In *Modeling Plant and Soil Systems*, pp. 439-455. Agronomy Monograph No. 31. Madison, Wisc.: ASA-CSSA-SSSA.

Willmott, C. J. (1981). On the validation of models. *Physical Geography, 2*(2), 184-194.

Zamora, D. S., Jose, S., Jones, J. W., & Cropper Jr, W. P. (2009). Modeling cotton production response to shading in a pecan alley cropping system using CROPGRO. *Agroforestry Syst., 76*(2), 423-435. http://dx.doi.org/10.1007/s10457-008-9166-x.