Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 162, Pages 61-78, December 2017

Calibration and Validation of CSM-CROPGRO-Cotton Model Using Lysimeter Data in the Texas High Plains

*P. Adhikari[1], P.H. Gowda[2], G.W. Marek[3], D.K. Brauer[3], I. Kisekka[4],
B. Northup[2], and A. Rocateli[1]

[1]*Oklahoma State University, Stillwater, OK*
[2]*USDA-ARS Grazinglands Research Laboratory, EL Reno, OK*
[3]*USDA-ARS Conservation and Production Research Laboratory, Bushland, TX*
[4]*University of California Davis, CA*
**Corresponding Author*

Abstract: Texas High Plains (THP), one of the most important food and fiber producing regions in the Ogallala Aquifer Region, currently faces rapid decline of groundwater levels. Predicted climate extremes and high temporal variability in growing season precipitation may require growers to pump more groundwater from the Ogallala Aquifer to meet higher crop water demand. The Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM) is a widely used crop simulation tool for evaluating impacts of different water and crop management practices, including irrigation on crop yield and water use efficiency. In this study, CROPGRO-Cotton module of the DSSAT was calibrated and validated using 2000, 2001, 2002, and 2010 irrigated lysimeter field data managed by the USDA-ARS (United States Department of Agriculture - Agricultural Research Service) Conservation and Production Research Laboratory at Bushland, TX. The lysimeter field consisted of four equal plots designated as NE, SE, NW, and SW. Crop growth characteristics including leaf area index (LAI), above ground biomass (AGB), evapotranspiration (ET), soil moisture, and lint yield of 2000-NE, 2000-SE, and 2001-NE, were used for calibration and 2002-NE, 2010-NE, and 2010-SE were used for validation. The calibrated and validated model was used to simulate the long term (1924-2012) crop yield and seasonal crop ET. During the calibration process, some of the cultivar and ecotype parameters that influence LAI, AGB, and lint yield were adjusted for better statistical results. Measured and simulated LAI, AGB, ET, soil moisture, and lint yield showed good agreement during calibration and validation as indicated by performance statistics such as r^2 from 0.70 to 0.82, and percent error (PE) = -0.85 to 17.3% for LAI; r^2 = 0.89 to 0.95, and *PE* = -7.36 to -13.66% for AGB; and r^2= 0.90 to 0.94, and PE = 3.20 to 3.44% for ET during calibration and validation, respectively. The model underestimated ET during peak vegetative growth and development stage except in some circumstances. The calibrated and validated model was able to simulate lint yield and seasonal ET during a long term (1924-2012) historic period for Bushland, TX, under irrigated conditions. The calibrated model could be used to schedule ET based irrigation management practices in the THP and to estimate future ET for other modeling experiments.

Keywords: *crop model, DSSAT, above ground biomass, leaf area index, soil moisture, evapotranspiration, Ogallala Aquifer, cropping system model*

Cotton (*Gossypium hissutum* L.) is one of the most important fiber crops for the textile industry and also provides seed for animal and oil industries. Among several major cotton producing countries, USA is the leading exporter of cotton. Texas High Plains (THP) is one of the major cotton producing regions of the U.S., contributing about 25% of total U.S. cotton production (USDA 2012). About 95% of the water used for irrigation in the THP is pumped from the Ogallala Aquifer, one of the largest freshwater aquifers in the world (HDR 2001). Due to excessive groundwater pumping for irrigation, annual withdrawal has outpaced natural recharge, resulting in large declines in the amount of water available for irrigation and increased groundwater pumping costs (Nieswiadomy 1985; Musick et al. 1988; Colaizzi et al. 2009; Adusumilli et al. 2011). Numerous researchers (Scanlon et al. 2002; Sophocleous 2010; Haacker et al. 2016) have reported that ongoing depletion of the Ogallala Aquifer poses major challenges for crop production in the THP. In addition, researchers (Adams et al. 1998; Adhikari et al. 2016) also predict future reduced precipitation and warmer summer temperatures in the THP. It is expected in the coming decades that there will be a gradual shift in cotton production from irrigated to dryland/rainfed management. Therefore, the development and implementation of better irrigation management practices based on a critical understanding of the interaction among soil processes, weather variables, and crop management practices is necessary.

The Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM) is a widely used tool and is capable of simulating crop growth stage, development, and yield in response to the variability in agrometeorological conditions, soil properties, and management practices (Thorp et al. 2008; Hoogenboom et al. 2012). Using the field experimental data, a well calibrated DSSAT-CSM model could successfully be used to simulate crop response under various sets of experimental conditions, which can ultimately speed decision making by reducing the time and resources required for long term field experimentation. Numerous researchers (Rezzoug et al. 2008; Liu et al. 2011; Hoogenboom et al. 2012; Wajid et al. 2014; Kisekka et al. 2015; Adhikari et al. 2016; Attia et al. 2016, Mauget et al., 2017) have used DSSAT-CSM for different applications. Wajid et al. (2014) used the CSM-CROPGRO model to simulate development, growth, and seed cotton yield of four cotton cultivars under varying nitrogen fertilizer rates and planting dates in Pakistan. They reported that the simulated crop phenology, seed cotton yield, and total dry matter were reasonable when compared with the observed data. The CSM-CROPGRO-Cotton model was used to study the impact of El Niño Southern Oscillation (ENSO) based climate variability on crop water use efficiency across Alabama, Florida, and Georgia (Garcia y Garcia et al. 2010). The CSM-CROPGRO model combined with kriging was used by Guerra et al. (2007) to estimate the spatial distribution of monthly irrigation water use for cotton. Similarly, Ortiz et al. (2009) used the CROPGRO-Cotton model to study the impact of root-knot nematodes on cotton biomass in Tifton, Georgia; Cammarano et al. (2012) used CROPGRO-Cotton to evaluate the economics of cotton irrigation strategies in Australia; and Zamora et al. (2009) used CROPGRO to simulate cotton production under different light levels in a pecan alley cropping system in Jay, Florida. Recently, Modala et al. (2015) evaluated the CSM-CROPGRO model for the Texas Rolling Plains using the field experimental data on different levels of irrigation at different stages of cotton growth and used the calibrated model to identify and evaluate optimum deficit irrigation strategies for the region. Similarly, Adhikari et al. (2017) used the CROPGRO-Cotton model to access the impacts of winter wheat cover crops on the cotton production system of the Texas Rolling Plains. In the semi-arid climate of Southern Kansas, Araya et al. (2017) evaluated DSSAT-CSM for different crops such as corn, wheat, and grain sorghum for water limited cropping systems. They reported that the model was able to adequately simulate the onset of crop phonological stages such as flowering, maturity, crop yield, and above ground biomass (AGB) for these three crops. DSSAT-CSM was also used to study the impact of climate variability on various soil organic carbon and carbon mediated processes (Porter et al. 2010). Reddy et al. (2002) used the cotton simulation model GOSSYM to understand the implication of climate change on cotton production at Stoneville, Mississippi, USA. Most of these studies used field experimental data for only one or two crop growing seasons to calibrate and validate the DSSAT-CSM model. It is reported that using long term measured data and including calibration of the model for sensitive crop characteristics will not only enhance confidence in the model but also allow the user to evaluate crop and water management strategies under a wide range of climatic conditions. The current study used 2000, 2001, 2002, and 2010 cotton growing season data from large lysimeter fields managed by USDA-ARS Conservation and Production Research Laboratory at Bushland, TX. Measured crop characteristics data included leaf area index (LAI), AGB, lint yield, crop evapotranspiration (ET), and soil moisture. Use of crop ET measured during a field lysimeter study for calibration and validation processes increases the value of this study because crop ET is considered one of the most significant components of the hydrological process required for irrigation scheduling. To the best of our knowledge, only the CERES-Maize model (Marek et al. 2017) was calibrated using long term daily and seasonal lysimeter-based ET in the THP. Therefore, the objectives of the study were: 1) to calibrate and validate the CROPGRO-Cotton model using the long term lysimeter data during 2000, 2001, 2002, and 2010 under irrigated (sprinkler irrigation system) conditions, and 2) to use the calibrated CROPGRO-Cotton model to simulate long term (1924-2012) ET and lint yield.

Materials and Methods

Study Site

Measured data for this study during 2000, 2001, 2002, and 2010 cotton growing seasons were obtained from a field experiment conducted at the USDA-ARS Conservation and Production Research Laboratory at Bushland, TX (35.19° N, 102.10° W, 1170 m above MSL). Irrigated cotton was planted in the lysimeter study only during these years (2000, 2001, 2002, and 2010). The research area consisted of four, 4.7 ha subdivided fields designated as NE, SE, NW, or SW, each containing a centrally located weighing lysimeter. These fields were irrigated with a N-S oriented, ten-span, 457 m linear-move sprinkler irrigation system travelling E-W or W-E. Crop management data including cotton growth characteristics such as LAI, AGB, lint yield, daily ET, and soil moisture during 2000-NE, 2000-SE, 2001-NE, 2002-NE, 2010-NE, and 2010-SE cotton growing seasons and fields were obtained. Adjacent to the lysimeter fields is a 1,760 m^2 irrigated, mowed grass reference ET weather station, maintained in accordance with the American Society of Civil Engineers (ASCE) - Environmental and Water Resource Institute (EWRI) specifications (Walter et al. 2005). The soil texture in the study site is characterized as deep, well drained Pullman silty clay loam soil (fine, mixed, superactive, thermic Torrertic Paleustoll) (Marek et al. 2016a). Soil data needed for the study were obtained from a recent modeling study conducted at Bushland, TX (Marek et al. 2016a). More detailed descriptions about the soil, the lysimeter field study, and the lysimeter setup can be found elsewhere (Marek et al. 2016a; 2016b). Soil moisture at different depths during different cotton growing seasons was measured using neutron probes. Details on the procedure and measurement of soil moisture using neutron probes in the lysimeter field are provided by Evett et al. (2003) and Evett (2008).

DSSAT-CROPGRO-Cotton Cropping System Model

The CSM-CROPGRO-Cotton model distributed with the DSSAT was calibrated and validated using field measured lysimeter data over a range of cotton growing seasons (2000, 2001, 2002, and 2010). The DSSAT integrates a database management system (soil, climate, and management practices) and crop models with various application programs (Hoogenboom et al. 2012). It brings together 42 individually developed crop models to a single platform. The latest DSSAT 4.6.1.0 version was used in the current study. The CROPGRO-Cotton model predicts cotton growth, LAI, AGB, ET, yield, and soil water content in response to weather, soil type, crop management practices, and crop cultivars. Model default Priestley-Tylor method was used to estimate ET. The model also estimates various crop development stages such as emergence, first leaf, first flower, first seed, first crack boll, and 90% open boll. The CROPGRO-Cotton model requires various soil parameters such as percent sand, clay, stone, organic carbon, pH, cation exchange capacity, slope, albedo, color, drainage, drained upper limit (DUL), lower limit (LL), saturated water content (SAT), hydraulic conductivity, organic carbon content, bulk density, total soil nitrogen, root growth factor (SRGF), and soil fertility factor (SLPF) (Jones et al. 2003). Based on the initial soil moisture provided in the soil file, DSSAT computes daily soil water balances required to simulate soil water content (Ritchie and Otter 1985). Daily soil water balance is calculated using the following equations (Jones et al. 2003; Jiang et al. 2016):

$$\Delta S = I + P - D - R - T - S_{Evap} - ET_{Mulch} \tag{1}$$

where ΔS is change in soil water (mm), I is amount of irrigation (mm), P is precipitation (mm), D is drainage (mm), R is runoff (mm), T is transpiration (mm), S_{Evap} is soil evaporation (mm), and ET_{Mulch} is evaporation from the mulch surface (mm).

Model Input

Crop Management Data. The details of tillage, planting, fertilizer application, harvesting, and irrigation management practices adopted during 2000, 2001, 2002, and 2010 cotton growing seasons are presented in Table 1. Each lysimeter field was prepared with tillage practices that included shredding stalks, reshaping beds with a rolling cultivator, and furrow diking between late March and mid-May of each year. Experienced scientists and support staff were involved in implementing field operations and collecting agronomic practices including planting, tillage, irrigation, fertilization, plant sampling, LAI measurement, and soil water measurement. The Paymaster 2145 cotton seed variety was planted in all years using a John Deere Maxemerge Planter at 4-cm depth. Cotton was harvested during a period between early October and mid November each year.

Climate Data. The DSSAT-CSM requires daily maximum and minimum temperature (˚C), incoming solar radiation (MJ m^{-2} d^{-1}), and precipitation (mm) to simulate crop growth and development. Data on wind speed (m km^{-1}), dew point temperature (˚C), and relative humidity (%) are optional. Daily weather parameters for the current study, including daily maximum and minimum temperature, incoming solar radiation, precipitation, wind speed, and relative humidity (%) during 2000 to 2010, were obtained from the USDA-ARS Soil and Water Management Research Unit (SWMRU), Bushland, TX. Missing weather data were obtained from the Texas High Plains Evapotranspiration Network (TXHPET) (Porter et al. 2005) at Bushland, TX weather station. The QA/QC techniques were applied to weather datasets to ensure valid data following the procedure suggested by Marek et al. (2016a). The DSSAT-CSM weather module was used to arrange all the weather data in the standard format.

Table 1. Selected crop management practices during calibration and validation periods.

Year	Planting Date	Harvest Date	Seed Rate (seed ha^{-1})	Irrigation (mm)	Cultivar	Fertilizer (kg ha^{-1}) N-P-K
-----------------Calibration-----------------						
2000-NE	5/16/2000	10/6/2000	89600	292	PAYM2145	50-75-0
2000-SE	5/16/2000	10/6/2000	95200	519	PAYM2145	50-75-0
2001-NE	5/16/2001	10/3/2001	95200	212	PAYM 2145	50-75-0
------------------Validation------------------						
2002-NE	5/21/2002	11/13/2002	89600	494	PAYM2145	168-50-0
2010-NE	5/26/2010	10/28/2010	91840	290	PAYM 2145	120-40-0
2010-SE	5/26/2010	10/28/2010	91840	275	PAYM 2145	120-40-0

Long term (1924-2012) weather data, including minimum and maximum temperature, precipitation, solar radiation, wind speed, and relative humidity, were compiled from TXHPET, USDA-ARS, and National Climatic Data Center (NCDC) datasets. Solar radiation and relative humidity were available from 1990 onwards only. Daily solar radiation for the period prior to 1990 was estimated from the measured maximum and minimum temperature (Hunt et al. 1998). Relative humidity data collected prior to 1990 and wind speed data collected prior to 1963 used in this study were generated using the weather generator in Soil Water Assessment Tool (SWAT), as a part of another study.

Model Calibration and Validation

Crop management data for cotton growing seasons 2000-NE, 2000-SE, and 2001-NE were used for calibration and data from 2002-NE, 2010-NE, and 2010-SE were used for validation. These specific years and locations were selected because only during these years was irrigated cotton grown in the lysimeter fields. Different projects were created with the available crop management practices (Table 1) such as planting date, seed rate, fertilizer application, irrigation, and harvesting. Simulated plant growth characteristics such as LAI, AGB, onset of cotton phenological stages, crop ET, lint yield, and soil moisture were compared against measured data. Since the DSSAT cultivar database did not include the Paymaster 2145 variety, it was added as a new cultivar in the DSSAT cultivar database and its parameters were populated based on the literature values for the THP (Robertson et al. 2007). Some of the cultivar parameters were later adjusted during model calibration. Several other input parameters that govern the crop growth, development, and yield were adjusted manually to improve the model simulation results. The model evaluation was carried out in six steps. Initially, the simulated dates of various cotton phenological stages were compared with actual dates, followed by LAI, AGB, ET, soil moisture, and finally, lint yield. The effect of each adjusted parameter (or growth stage) was studied by graphically comparing simulated and measured lint yield (time series plots). Performance statistics parameters used in this study were coefficient of determination (r^2) (Legates and McCabe 1999), root mean square error (*RMSE*), index of agreement (*d*) (Willmott et al. 1985), and percent error (*PE*), which were calculated using equations 2, 3, 4, and 5, respectively. The r^2 values range between 0 and 1, with 0 indicating "no fit" and 1 indicating "perfect fit" between the simulated and observed values. The *RMSE* values closer to 0 indicate better agreement between the simulated and observed values. The *d* values range between 0 (no agreement) and 1 (perfect fit). The value of *PE* ranges from -100 to ∞, and absolute *PE* values closer to 0 indicate better agreement.

$$r^2 = \frac{\left(\sum_{i=1}^{N}\left(Yi - \overline{Y}\right)\left(\hat{Y}i - \overline{Y}i\right)\right)^2}{\sum_{i=1}^{N}\left(Yi - \overline{Y}\right)^2 \sum_{i=1}^{N}\left(\hat{Y}i - \overline{Y}i\right)^2} \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(\hat{Y}i - Yi)^2}{N}} \tag{3}$$

$$d = 1 - \left[\frac{\sum_{i=1}^{N}\left(Y_i - \overline{Y}_i\right)^2}{\sum_{i=1}^{N}\left(\left|\hat{Y}_i - \overline{Y}\right| + \left|Y_i - \overline{Y}\right|\right)^2}\right], 0 \leq d \geq 1 \tag{4}$$

$$PE = \left(\sum_{r=1}^{N}\frac{\hat{Y}i - Yi}{Yi}\right)x100 \tag{5}$$

where Yi = observed value, $\hat{Y}i$ = simulated value, $\overline{Y}i$ = average of simulated value, $\overline{Y}$ = average of observed value, and N = number of observations.

The model calibration effort was carried out until the resultant *RMSE* was low, and r^2 and *d* were higher than 0.80. Twelve cultivar parameters and five ecotype parameters were adjusted until the simulated crop development stages, LAI, AGB, ET, soil moisture, and lint yield matched reasonably well with measured data (Table 2).

Long Term Simulation

Long term (1924-2012) weather data were used to simulate lint yield with the calibrated and validated DSSAT-CROPGRO-Cotton model at Bushland, TX. Long term simulations are important to understanding the changes that occur in the environment, their possible impacts on crop production, and the subsequent implementation of crop management decisions. A common planting

Table 2. Comparison of simulated and generally observed dates of onset of cotton phenological stages.

Crop phenological stage	Observed* (days after planting)	Simulated (days after planting)		
------------------Calibration------------------				
		2000-NE	2001-NE	2000-SE
Emergence	4 – 9	4	4	4
Anthesis	60 – 70	63	63	63
Physiological maturity	130 – 160	135	143	139
------------------Validation------------------				
		2002-NE	2010-NE	2010-SE
Emergence	4 – 9	5	4	4
Anthesis	60 – 70	64	64	68
Physiological maturity	130 – 160	155	146	146

*Robertson et al. 2007.

date of May 16th was assumed for all historic (1924-2012) simulations. Similar management practices such as tillage, fertilizer application, and seeding rate were used every year throughout the 89 years of simulations. The automatic sprinkler irrigation method was implemented by triggering irrigation when the simulated soil moisture was depleted to 50% of available soil water content, and irrigation continued until the soil profile moisture measured 85% of available soil water capacity. In addition, 89 years of long term, historic (1924-2012) data were divided into dry (0-200 mm), normal (201-400 mm), and wet years (> 400 mm), according to the growing season precipitation.

Results and Discussion

Model Evaluation

The simulated dates of onset of various cotton phenological stages at Bushland, TX, such as emergence, anthesis, and physiological maturity during calibration and validation, are presented in Table 2. During both calibration and validation years, simulated emergence, anthesis, and physiological maturity dates were within the observed range (Robertson et al. 2007). In a recent study, Adhikari et al. (2016) also observed similar range of anthesis and physiological maturity days in the THP. Although the simulated physiological maturity dates varied in different years, they were typically within the observed range. The differences in maturity date might have been due to the differences in planting date, photothermal duration, precipitation, and other weather-related parameters during growing seasons. For instance, maturity days during the 2010 growing season were shorter compared to the 2002 cotton growing season. Shorter duration of physiological maturity during 2010 may be attributed to higher air temperatures and lower precipitation measured during that year. For the years of 2002 and 2010, seasonal (121 Days-Of-Year (DOY) to 273 DOY) average maximum temperature was 31.4 ˚C and 32.1 ˚C, respectively, whereas total seasonal rainfall was 205.5 mm and 184.5 mm, respectively. Similarly, seasonal average minimum temperature was 16.9 ˚C during 2002 and 16.8 ˚C during 2010. Low rainfall and higher average maximum temperature during the 2010 growing season might have led to faster development of cotton with shorter time interval between developmental stages.

The calibrated values of cultivar and ecotype parameters for the study site are shown in Table 3. Since observed data, such as LAI and AGB, were available, the cotton cultivar parameters were adjusted to reasonably estimate LAI and AGB after achieving reasonable prediction of onset of crop phenological stage over the growing seasons. Parameters adjusted for Paymaster 2145 cotton cultivars were comparable to that in the DSSAT cultivar file. The adjusted photothermal duration between first flower and first seed (FL-SD) and photothermal duration between plant emergence and flower appearance (EM-FL) was greater than the previously determined values for 'Deltapine 77' and 'Deltapine 555' cultivars. However, photothermal duration between first flower and first pod (FL-SH) were lower than the previously determined values for 'Deltapine 77' and 'Deltapine 555' cultivars. The parameters of the cotton cultivars, such as FL-SD and FL-SD, were adjusted to accurately simulate the crop yield, and the EM-FL parameter, important for accurately predicting the onset of flowering, was tested within a range of 34-48 photothermal days and a value of 41 photothermal days, at which the model simulated reasonable flowering dates, was selected. Previously reported, calibrated values of EM-FL varied between 45 and 51 days, depending on geographical locations and crop management practices. A modeling study conducted by Ortiz et al. (2009) at Tifton, GA, reported an EM-FL value of 45 photothermal days for Deltapine 485/BG/RR cotton cultivar. Similarly, Thorp et al. (2014) obtained calibrated EM-FL values that ranged between 46 and 51 for cotton at Maricopa, AZ. The differences in EM-FL value obtained in this study, when compared to previous studies, might have been due to the differences in weather conditions as well as crop management practices. Cultivar parameters were adjusted as needed; SD-PM was adjusted to 40 photothermal days to simulate the crop harvesting date accurately, and FL-LF was adjusted to 55 days to correctly simulate the end of leaf growth (Table 3). Other cultivar parameters that influence photosynthesis rate, transpiration, and assimilation of carbon in the cotton plant included maximum leaf photosynthesis rate (LFMAX), specific leaf area (SLAVR), and maximum size of full leaf (SIZLF). During the final stage, cultivar parameters such as maximum fraction of daily growth that is partitioned to seed + shell (XFRT), seed filling duration for pod cohort (SFDUR), time required to reach final pod load (PODUR), and threshing percentage (THRSH) were adjusted for obtaining a better comparison between measured and simulated lint yield (Table 3). The ecotype parameters adjusted included relative width of the ecotype in comparison to the standard width per node (RWDTH), adjusted to correctly simulate canopy width, relative height of the ecotype in comparison to the standard height per node (RHGHT), adjusted for canopy height, and FL-VS, adjusted for cessation of stem elongation.

Leaf Area Index (LAI) and Above Ground Biomass (AGB)

The CSM-CROPGRO-Cotton model predicted LAI well during calibration, as indicated by good agreement between measured and simulated LAI (Fig.1a-c) and good model performance statistics (Table 4). The performance statistics indicated that r^2 was 0.70, *d* was 0.87, and *PE* was 17.3% for calibration. The model overpredicted LAI between 189 DOY and 214 DOY, and underpredicted between 214 DOY and ~250 DOY (Fig. 1a & c) during 2000-NE and 2000-SE calibration years. However, during 2001-NE calibration year the model overpredicted LAI between 183 DOY and ~200 DOY and underpredicted between ~201 DOY and 247 DOY (Fig. 1b). Thorp et al. (2014) also reported mixed underpredicted and overpredicted LAI with the CROPGROP-Cotton model when comparing data measured at University of Arizona, Maricopa Agricultural Center, during a 1990 free-air carbon dioxide enrichment (FACE) experiment, due to the differences in the ambient atmospheric CO_2 during the cotton growing seasons. Similarly, underestimated LAI was reported by Ortiz et al. (2009) in their study to simulate growth and yield of cotton plants infected with root knot nematodes using the CROPGRO-Cotton model.

Simulated LAI matched very well with measured LAI (Fig. 2a-c) during validation years. The performance statistics indicated that r^2 was 0.82, *d* was 0.91, and *PE* was 0.85%. Similar to the calibration, the model overestimated LAI

Table 3. Parameters adjusted during the CROPGRO-Cotton module calibration.

Cultivar parameters		**Testing range**	**Calibrated value**
EM-FL	Time between plant emergence and flower appearance (photothermal days)	34-48	41
FL-SH	Time between first flower and first pod (photothermal days)	1-12	3
FL-SD	Time between first flower and first seed (photothermal days)	3-18	5
SD-PM	Time between first seed and physiological maturity (photothermal days)	32-50	40
FL-LF	Time between first flower and end of leaf expansion (photothermal days)	45-75	55
LFMAX	Maximum leaf photosynthesis rate at 30 ºC, 350 ppm CO2, and high light (mg CO2 m-2 s-1)	0.2-2	1.0
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm2 g-1)	110-200	170
SIZLF	Maximum size of full leaf (three leaflets) (cm2)	100-350	250
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.3-1	0.70
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	15-45	35
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	4-16	8
THRSH	Threshing percentage. The maximum ratio of (seed/(seed+shell)) at maturity	40-75	60
Ecotype parameters		**Testing range**	**Calibrated value**
PL-EM	Time between planting and emergence (thermal days)	1-5	2
EM-V1	Time required from emergence to first true leaf (thermal days)	2-6	4
RWDTH	Relative width of the ecotype in comparison to the standard width per node	0.8-1.0	0.95
RHGHT	Relative height of the ecotype in comparison to the standard height per node	0.8-1.5	1
FL-VS	Time from first flower to last leaf on main stem (photothermal days)	30-75	40

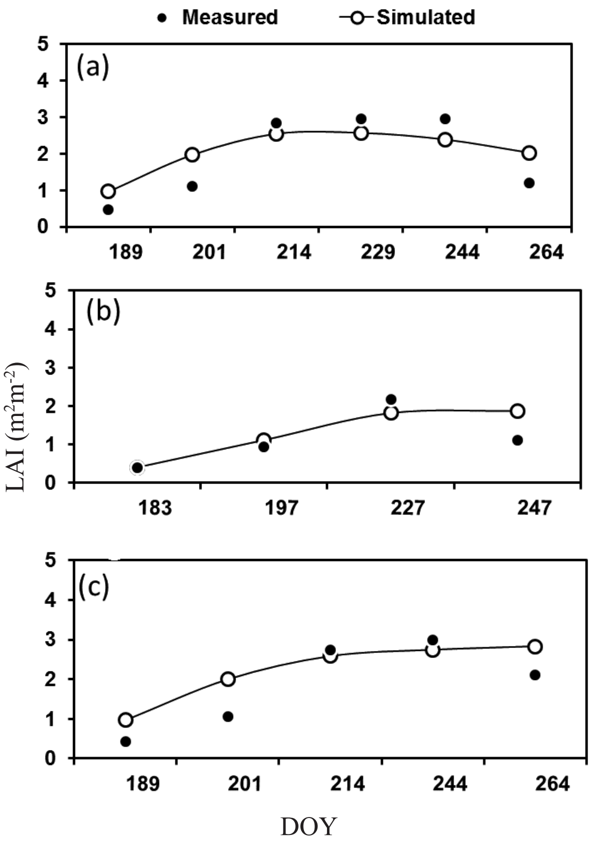

Figure 1. Comparison between measured and simulated leaf area index (LAI) of cotton during different calibration years (a) 2000-NE, (b) 2001-NE, and (c) 2000-SE.

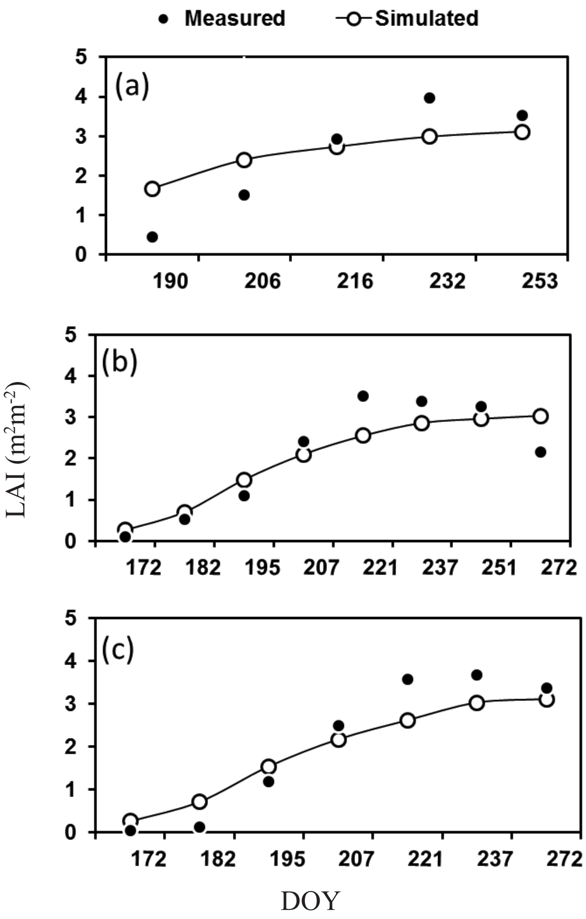

Figure 2. Comparison between measured and simulated leaf area index (LAI) of cotton during different validation years (a) 2002-NE, (b) 2010-NE, and (c) 2010-SE.

between 190 DOY and 216 DOY during 2002-NE validation year, and 172 DOY and 207 DOY during 2010-NE and 2010-SE validation years, considered to be the vegetative growth and development stage. However, the model underestimated LAI between 216 DOY and 253 DOY during 2002-NE; between 207 DOY and 237 DOY (Fig. 2b-c) is considered to be maturity stage. The average measured LAI was 2.98 m^2 m^{-2} during calibration and 2.20 m^2 m^{-2} during validation, whereas simulated LAI was 2.83 m^2 m^{-2} and 2.12 m^2 m^{-2}, respectively.

Similar to LAI, the CSM-CROPGRO-Cotton model predicated AGB very well during both calibration and validation periods (Figs. 3 & 4). The performance statistics during calibration and validation periods are presented in Table 4. During 2000-NE calibration year (Fig. 3a) the model slightly overestimated AGB during early vegetative growth and development stage to maturity and underestimated during senescence, which was in accordance with the LAI. The model estimated AGB perfectly between 183 DOY and ~210 DOY during 2001-NE, and between 189 DOY and ~210 DOY during 2000-SE calibration years. However, the model overestimated during maturity stage (Fig. 3b-c) on both years. During validation years the model overestimated AGB during early growth and development stage and underestimated during maturity (Fig. 4a-c). Similar to our experiments, Ortiz et al. (2009) reported overestimated AGB during early maturity when using the CROPGRO-Cotton model. The average measured AGB during calibration and validation period was 7498 kg ha^{-1} and 3555 kg ha^{-1} and simulation was 5699 kg ha^{-1} and 3050 kg ha^{-1}, respectively.

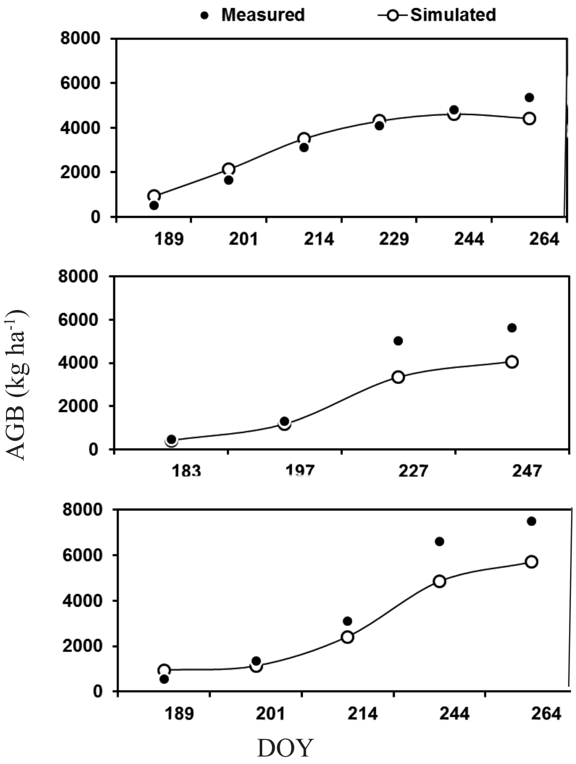

Figure 3. Comparison between measured and simulated above ground biomass (AGB) of cotton during different calibration years (a) 2000-NE, (b) 2001-NE, and (c) 2000-SE.

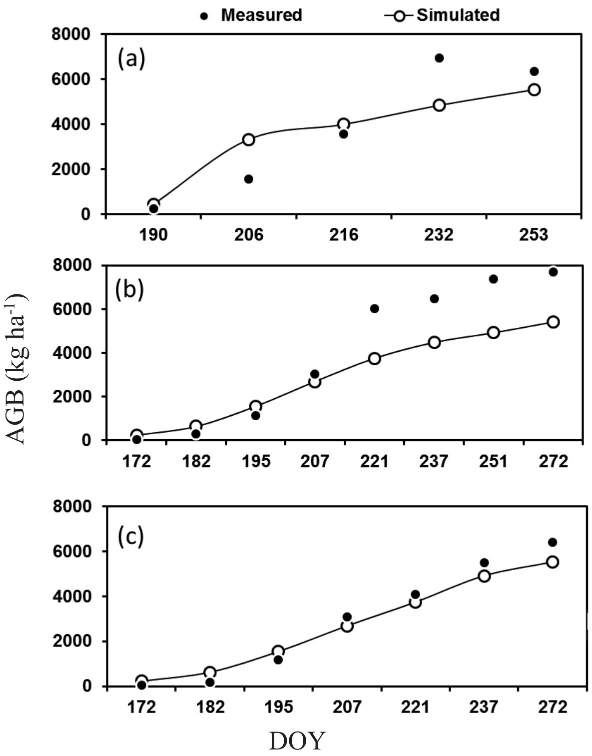

Figure 4. Comparison between measured and simulated above ground biomass (AGB) of cotton during different validation years (a) 2002-NE, (b) 2010-NE, and (c) 2010-SE.

Table 4. Comparison statistics between measured and simulated leaf area index (LAI), above ground biomass (AGB), evapotranspiration (ET), soil moisture at 0-20 cm depth, and lint yield during model calibration (2000-NE, 2000-SE, and 2001-NE) and validation (2002-NE, 2001-NE, and 2010-SE).

	r^2	*RMSE*	*d*	*PE (%)*
	Calibration			
LAI (m^2 m^{-2})	0.70	2.4	0.87	17.3
AGB (kg ha^{-1})	0.95	1.3	0.96	-7.36
ET (mm d^{-1})	0.94	0.7	0.98	3.2
Soil moisture (mm^3 mm^{-3})	0.77	2.80	0.75	7.47
Lint yield (kg ha^{-1})	0.93	1.66	0.97	1.45
	Validation			
LAI (m^2 m^{-2})	0.82	1.5	0.91	-0.85
AGB (kg ha^{-1})	0.89	1.6	0.93	-13.66
ET (mm d^{-1})	0.90	1.02	0.96	3.44
Soil moisture (mm^3 mm^{-3})	0.71	2.15	0.72	22.31
Lint yield (kg ha^{-1})	0.94	2.37	0.96	8.61

Where r^2 coefficient of determination, *RMSE* is Root Mean Square Error, *d* is index of agreement, and *PE* is Average Percent Error.

Evapotranspiration

Measured daily ET values from the lysimeter experiment were very close to the simulated seasonal ET values by the DSSAT-CROPGRO-Cotton model during both calibration and validation periods (Figs. 5 and 6). Similar to our results, Thorp et al. (2014) observed good agreement between measured and simulated ET in the FACE experiment conducted at Maricopa, Arizona, using the CROPGRO-Cotton model. The performance statistics for the comparison of measured and simulated ET during calibration and validation periods are presented in Table 4. During the 2000-NE calibration year the model underestimated the daily ET during emergence periods. Similarly, in the later stage of cotton growing seasons (218 to 240 DOY) the model over predicated ET, which was in accordance with LAI (Fig. 1a). Similar to 2000-NE calibration year, the model under simulated ET between 141 DOY and 150 DOY during 2001-NE, and between 137 DOY and ~150 DOY during 2000-SE, considered as the emergence of the cotton (Fig. 5b-c). During peak vegetative growth stage, the model underestimated ET during 2000-SE years (Fig. 5c) which was associated with the under prediction of LAI during that period. During validation years (Fig. 6a-c) the model underestimated ET during emergence, initial growth stage, and peak vegetative growth stage, and overestimated near maturity stage in all validation years. During 2002-NE validation year the model underestimated ET during 138 DOY to 152 DOY, 210 DOY to 240 DOY, and some other occasions. During 2010-NE and 2010-SE validation years the model underestimated ET from 138 DOY to 160 DOY, considered the early growth stage of cotton. The model also underestimated ET from 201 DOY to 256 DOY and during some occasions during the 2010-NE and 2010-SE validation years, which was associated with lower LAI (Fig. 2a-c). The overestimation of ET by the model when there was underestimated LAI and vice versa might be due to differences in the canopy temperature and air temperature. The CROPGRO-Cotton model assumes air temperature as the canopy temperature, which is the major limitation of

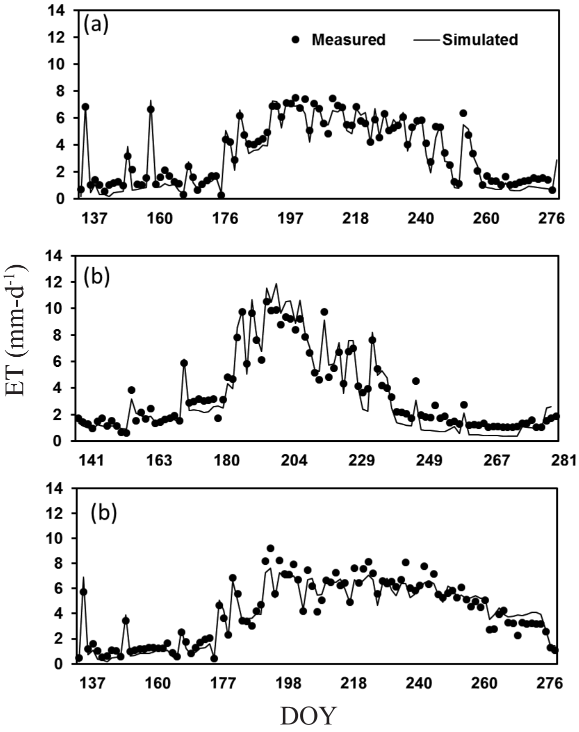

Figure 5. Comparison between measured and simulated daily cotton evapotranspiration (ET) during calibration years (a) 2000-NE, (b) 2001-NE, and (c) 2000-SE.

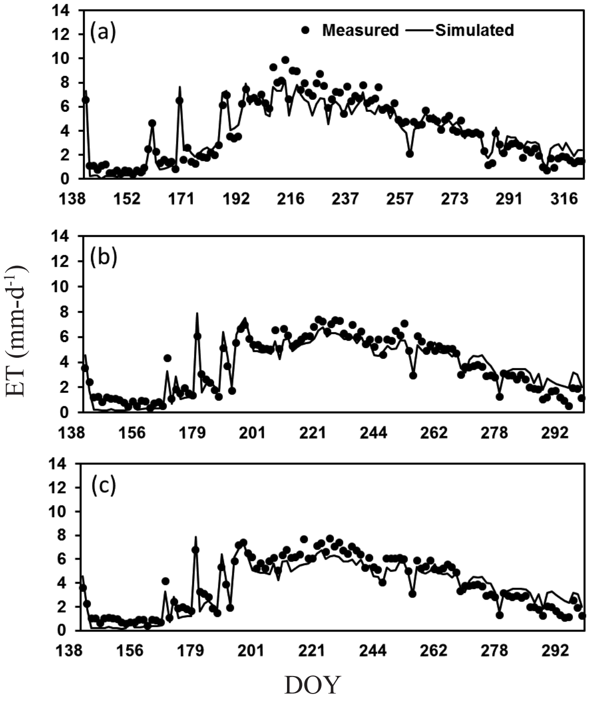

Figure 6. Comparison between measured and simulated daily cotton evapotranspiration (ET) during validation years (a) 2002-NE, (b) 2010-NE, and (c) 2010-SE.

this model. Usually canopy temperature is lower than the air temperature under well-watered conditions, due to evaporative cooling. Our study was conducted under irrigated conditions, and the difference in the canopy temperature and air temperature might have resulted in different simulated ET on those validation years. Average measured ET during calibration and validation were 3.76 and 3.86 mm d^{-1}, whereas simulated ET averages were 3.58 and 3.71 mm d^{-1}, respectively. Maximum measured (10.51 mm d^{-1}) and simulated (11.89 mm d^{-1}) ET were observed between 60-73 days after planting, during the peak vegetative growth stage.

Soil Moisture

Simulated and measured daily soil moisture including rainfall and irrigation amounts after cotton planting during calibration and validation years are presented in Figures 7 and 8. The CSM-CROPGRO-Cotton model predicted well the seasonal soil moisture content at 0-20 cm depth for both calibration (Fig. 7a-c) and validation (Fig. 8a-c) years. The model performance statistics such as r^2, d, and PE were 0.77, 0.75, and 7.47% during calibration and 0.71, 0.72, and 22.31% during validation, respectively. The corresponding values of RMSE were 2.81 mm^3 mm^{-3} and 2.15 mm^3 mm^{-3} during calibration and validation periods, respectively. The model responded very well with rainfall and precipitation events. For instance, the rainfall event of 35 mm occurred during 177 DOY of 2000 (Fig. 7a) and increased soil moisture from 0.19 mm^3 mm^{-3} to 0.35 mm^3 mm^{-3}. During calibration years (2000-NE, 2000-SE, and 2001-NE), average measured seasonal soil moisture at 0-20 cm depth ranged between 0.19 mm^3 mm^{-3} and 0.22 mm^3 mm^{-3}, whereas simulated average soil moisture at the same depth ranged between 0.17 mm^3 mm^{-3} and 0.20 mm^3 mm^{-3}. During validation years, (2002-NE, 2010-NE, and 2010-SE), average measured seasonal soil moisture ranged from 0.20 mm^3 mm^{-3} to 0.22 mm^3 mm^{-3} and simulated soil moisture ranged from 0.16 mm^3 mm^{-3} to 0.18 mm^3 mm^{-3} at 0-20 cm depth.

Lint Yield

The performance statistics between measured and simulated lint yield indicated by r^2, d, and PE were 0.93, 0.97, and 1.45% for calibration and 0.94, 0.96, and 8.61% for validation, respectively (Table 4). The CSM-CROPGRO-Cotton model predicted lint yield very well for both calibration and validation periods (Fig. 9a-b). The measured and simulated lint yields were higher during 2010-SE and 2010-NE than those observed during 2002-NE during validation, and might be due to the differences in planting date and seed rate (Table 1). Pettigrew et al. (2009) reported that early planting reduced cotton seed germination by 16% in the experiment conducted at Stoneville, MS. Similarly, another experiment conducted at a Mississippi cotton farm reported lint yield declines of 2.35 kg d^{-1} after the actual cotton harvesting day (Parvin et al. 2005). In the current experiment, cotton was planted on 21 May and harvested on 13 November during 2002, whereas during 2010 cotton was planted on 26 May and harvested on 28 October. In addition, the seed rate was higher during 2010 as compared to the 2002 cotton growing season (Table 1). Respectively, average measured and simulated lint yield was 960 kg ha^{-1} and 1006 kg ha^{-1} during calibration and 748 kg ha^{-1} and 803 kg ha^{-1} during the validation period.

Long Term Yield Simulation

The calibrated DSSAT-CROPGRO-Cotton model simulated lint yield for a period from 1924-2012 under irrigated conditions (Fig. 10). The calibrated model is able to demonstrate the effect of auto irrigation during dry, normal, and wet years for lint yield. Due to the implementation of auto-irrigation in the model, during the years of very low seasonal precipitation the model still simulated comparable lint yield with normal years. For instance, during years 2001, 2011, and 2012, the seasonal rainfall was well below 100 mm (dry years), yet the model still simulated a comparable amount of lint yield with the wet year.

Simulated averages with standard deviations of lint yield, ET, seasonal rainfall, and auto-irrigation during dry, normal, and wet years are presented in Table 5. Due to the implementation of auto-irrigation, no water stress was observed on lint yield even during the dry years; however, the amount of irrigation varied greatly. During the dry years, the amount of irrigation water ranged between 325 mm and 518 mm, during normal years

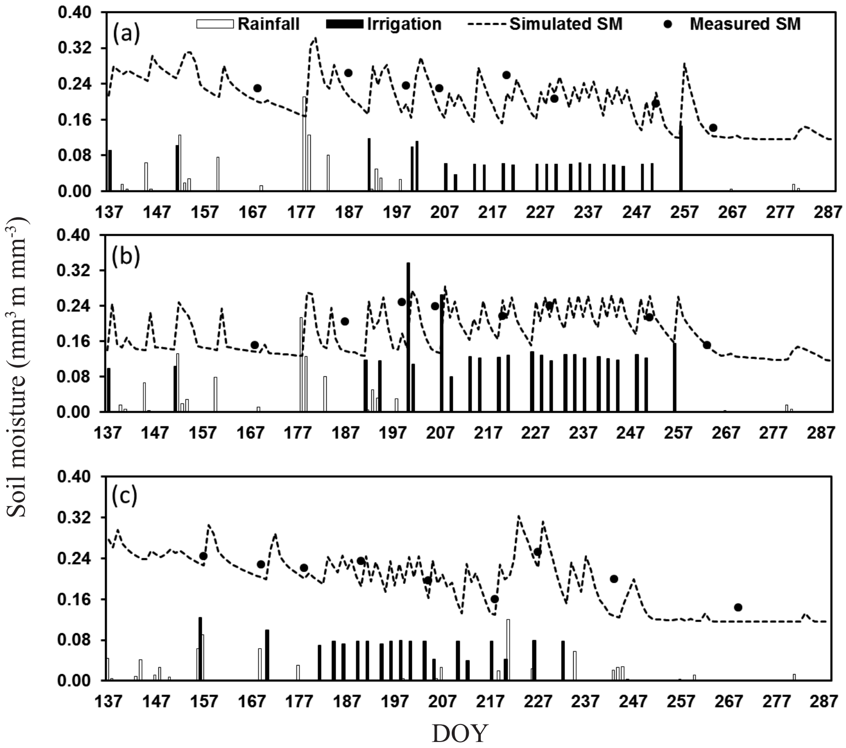

Figure 7. Comparison between measured and simulated daily soil moisture (SM) during calibration years (a) 2000-NE, (b) 2000-SE, and (c) 2001-NE at 0-20 cm depth.

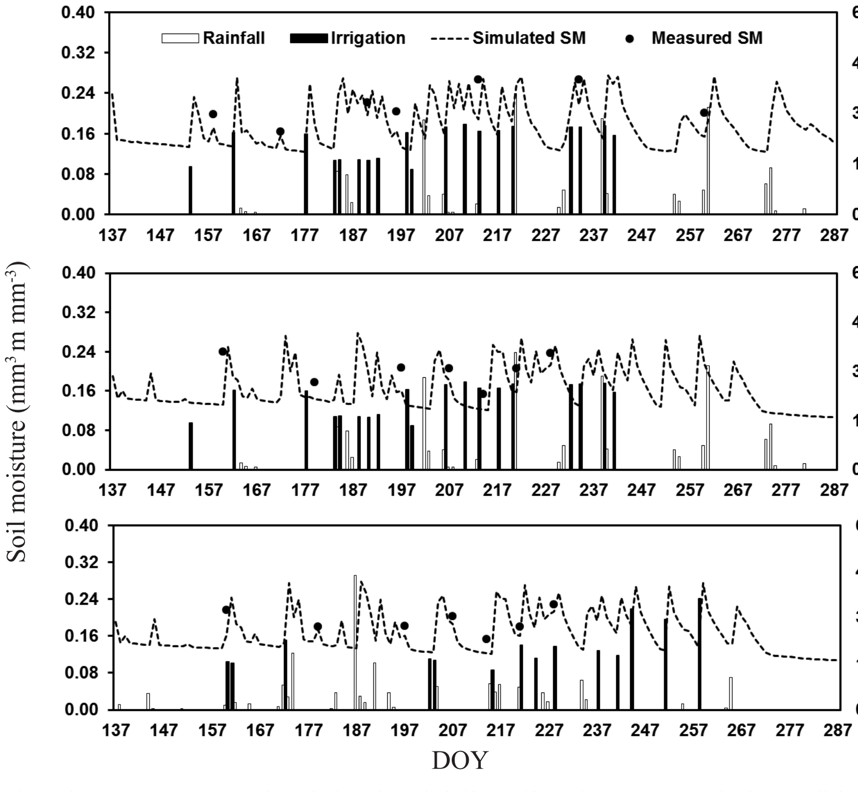

Figure 8. Comparison between measured and simulated daily soil moisture (SM) during validation years(a) 2002-NE, (b) 2010-NE, and (c) 2010-SE at 0-20 cm depth.

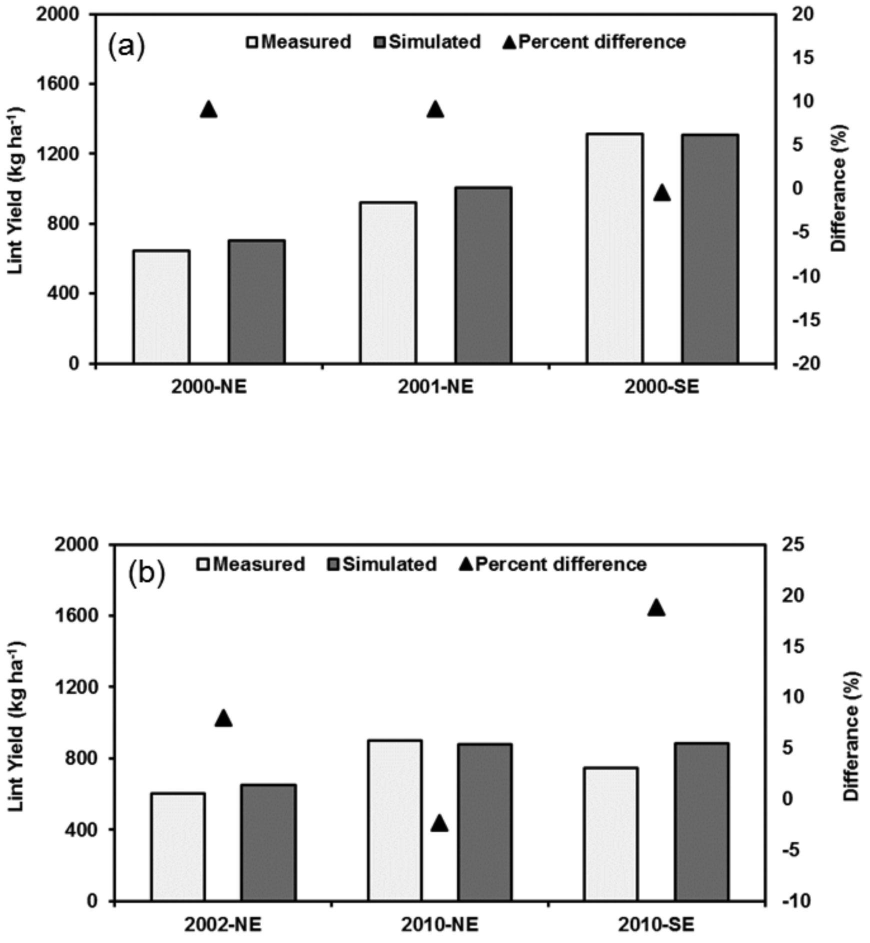

Figure 9. Comparison and percent difference between measured and simulated lint yield in the different cotton growing seasons during (a) calibration and (b) validation.

Table 5. DSSAT-CSM simulated historic (1924-2012) average with standard deviation of lint yield, evapotranspiration, seasonal rainfall, and auto-irrigation during dry, normal, and wet years at Bushland, TX.

	-------------- Irrigated --------------			
Years	**Average lint yield (kg ha^{-1})**	**ET (mm d^{-1})**	**Average seasonal rainfall (mm)**	**Auto-irrigation (mm)**
Dry years	615±88	567±28	132±50	419±57
Normal years	557±28	557±29	286±58	306±46
Wet years	629±169	570±29	493±84	208±35

between 218 mm and 403 mm, and during wet years between 118 mm and 348 mm. The results indicate that during dry years, an average of 37% more irrigating water was required when compared to normal years, and 99% more water was required compared to wet years. Simulated ET, lint yield, and auto irrigation under dry, normal, and wet years were least variable (CV<0.15). Rainfall and auto irrigation were moderately variable, with coefficients of variation (CV) ranging between 0.20 and 0.29, according to Wilding (1985) criteria (CV<0.15 as the least, 0-15<CV<0.35 as moderate, and CV>0.35 as the most variable).

Conclusions

A well-calibrated DSSAT-CROPGRO-Cotton model was established for the Bushland, TX study site, using field measured lysimeter data under irrigated conditions. The calibrated model is able to simulate crop phonological stages including LAI, AGB, ET, soil moisture, and lint yield. The simulated phonological stages such as emergence, anthesis, and physiological maturity date were within the range of the measured range for the THP regions. Twelve cultivar and five ecotype parameters were adjusted during the model calibration process. Good agreement was observed between measured and simulated LAI, AGB, seasonal ET, seasonal soil moisture, and lint yield during calibration and validation processes, as indicated by the performance statistics. The performance statistics for LAI during calibration were $r^2 = 0.82$, $d = 0.96$, and $PE = 0.19$ and were $r^2 = 0.93$, $d = 0.93$, and $PE = -3.74$ during validation. The calibrated model was able to simulate historic (1924-2012) lint yield during dry, normal, and wet years. During the dry years, THP cotton required an average of 37% and 99% more irrigation water when compared to normal and wet years, respectively. The results imply that there is a need for ET based irrigation management strategies in the THP, especially during the dry years, for which the current calibrated DSSAT-CROPGRO-Cotton model could be used.

Acknowledgements

Authors would like to thank Ogallala CAP project for funding this project.

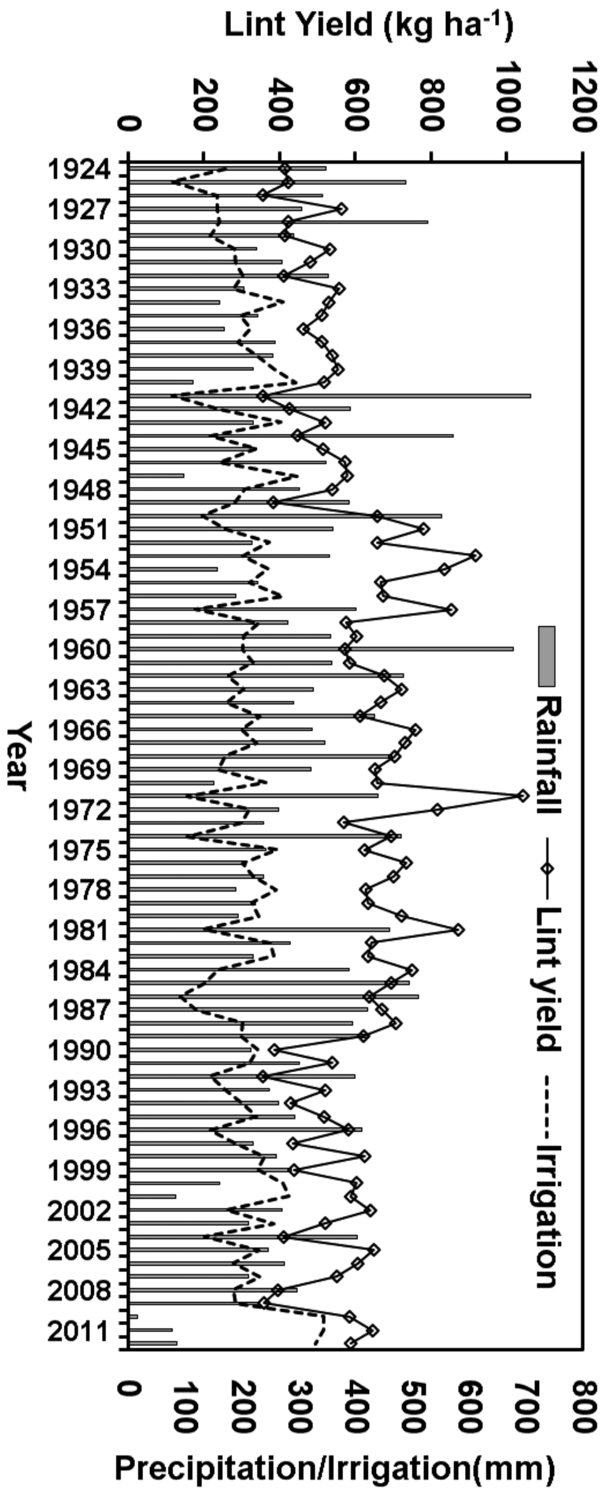

Figure 10. Simulated long term (1924-2012) lint yield (red line), auto irrigation (black line), and measured rainfall at Bushland, TX.

Author Bio and Contact Information

Pradip Adhikari (corresponding author) is a Post-doctoral Research Fellow at Oklahoma State University in Stillwater, Oklahoma. He can be reached at: USDA-ARS Grazinglands Research Laboratory, 7207 W. Cheyenne St., El Reno, OK 73036; or via email at Pradip.adhikari@okstate.edu.

Prasanna H. Gowda is a Research Leader at the Forage and Livestock Production Unit, USDA-ARS Grazinglands Research Laboratory in El Reno, OK. He can be reached at: USDA-ARS Grazinglands Research Laboratory, 7207 W. Cheyenne St., El Reno, OK 73036; or via email at Prasanna.Gowda@ars.usda.gov.

Gary W. Marek is a Research Agricultural Engineer at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas. He can be reached at: USDA-ARS Conservation and Production Research Laboratory, 2300 Experiment Station Road, Bushland, Texas; or via email at Gary.Marek@ars.usda.gov.

David K. Brauer is a Research Leader at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas. He can be reached at: USDA-ARS Conservation and Production Research Laboratory, 2300 Experiment Station Road, Bushland, Texas; or via email at david.brauer@ars.usda.gov.

Isaya Kisekka is Assistant Professor of Irrigation Engineering and Agricultural Water Management at the University of California Davis, California. He can be reached at: One Shields Avenue, PES 1110, Davis, CA; or via email at ikisekka@ucdavis.edu.

Brian Northup is a Research Ecologist at the Forage and Livestock Production Unit, USDA-ARS Grazinglands Research Laboratory in El Reno, OK. He can be reached at USDA-ARS Grazinglands Research Laboratory, 7207 W. Cheyenne St., El Reno, OK 73036; or via email at brian.northup@ars.usda.gov.

Alexandre C. Rocateli is Assistant Professor and Forage System Extension Specialist at Oklahoma State University in Stillwater, Oklahoma. He can be reached at: 366 Ag Hall, Stillwater, OK 74708; or via email at alex.rocateli@okstate.edu.

References:

Adams, R.M., B.H. Hurd, S. Lenhart, and N. Leary. 1998. Effects of global climate change on agriculture: An interpretative review. *Climate Research* 11(1): 19-30.

Adhikari, P., S. Ale, J.P. Bordovsky, K.R. Thorp, N.R. Modala, N. Rajan, and E.M. Barnes. 2016. Simulating future climate change impacts on seed cotton yield in the Texas High Plains using the CSM-CROPGRO-Cotton model. *Agricultural Water Management* 164: 317-330.

Adhikari, P., N. Omani, S. Ale, P.B. DeLaune, K.R. Thorp, E.M. Barnes, and G. Hoogenboom. 2017. Simulated effects of winter wheat cover crop on cotton production systems of the Texas Rolling Plains. *Transactions of the American Society of Agricultural and Biological Engineers* 60(6): x-xxx. DOI: 10.13031/trans.12272.

Adusumilli, N.C., M.E. Rister, and R.D. Lacewell. 2011. Estimation of irrigation water demand: A case study for the Texas High Plains. Selected Paper presented at the Southern Agricultural Economics Association Annual Meeting, February 11, 2011.

Araya, A., I. Kisekka, P.H. Gowda, and P.V.V. Prasad. 2017. Evaluation of water-limited cropping systems in a semi-arid climate using DSSAT-CSM. *Agricultural Systems* 150: 86-98.

Attia, A., N. Rajan, Q. Xue, S. Nair, A. Ibrahim, and D. Hays. 2016. Application of DSSAT-CERES-Wheat model to simulate winter wheat response to irrigation management in the Texas High Plains. *Agricultural Water Management* 165: 50-60.

Cammarano, D., J. Payero, B. Basso, P. Wilkens, and P. Grace. 2012. Agronomic and economic evaluation of irrigation strategies on cotton lint yield in Australia. *Crop Pasture Science* 63(7): 647.

Colaizzi, P.D., P.H. Gowda, T.H. Marek, and D.O. Porter. 2009. Irrigation in the Texas High Plains: A brief history and potential reductions in demand. *Irrigation and Drainage* 58(3): 257-274.

Evett, S.R. 2008. Neutron moisture meters. In: *Field Estimation of Soil Water: A Practical Guide to Methods, Instrumentation, and Sensor Technology*, S.R. Evett, L.K. Heng, P. Moutonnet, and M.L. Nguyen (Eds.). International Atomic Energy Agency, IAEA-TCS-30, Vienna, Austria, pp. 39-54.

Evett, S.R., J.A. Tolk, and T.A. Howell. 2003. A depth control stand for improved accuracy with the neutron probe. *Vadose Zone Journal* 2(4): 642-649.

Garcia y Garcia, A., T. Persson, J.O. Paz, C. Fraisse, and G. Hoogenboom. 2010. ENSO-based climate variability affects water use efficiency of rainfed cotton grown in the southeastern USA. *Agriculture, Ecosystems & Environment* 139(4): 629-635.

Guerra, L.C., A. Garcia y Garcia, J.E. Hook, K.A. Harrison, D.L. Thomas, D.E. Stooksbury, and G. Hoogenboom. 2007. Irrigation water use estimates based on crop simulation models and kriging. *Agricultural Water Management* 89(3): 199-207.

Haacker, E.M.K., A.D. Kendall, and D.W. Hyndman. 2016. Water level declines in the High Plains Aquifer: Predevelopment to resource senescence. *Groundwater* 54(2): 231-242.

HDR, E., Inc. 2001. Llano Estacado Regional Water Planning Area Regional Water Plan. Prepared for Llano Estacado Water Planning Group, Lubbock, Texas.

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

Hunt, L.A., L. Kuchar, and C.J. Swanton. 1998. Estimation of solar radiation for use in crop modelling. *Agricultural and Forest Meteorology* 91(3): 293-300.

Jiang, Y., L. Zhang, B. Zhang, C. He, X. Jin, and X. Bai. 2016. Modeling irrigation management for water conservation by DSSAT-Maize model in arid northwestern China. *Agricultural Water Management* 177: 37-45.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. The DSSAT cropping system model. *European Journal of Agronomy* 18(3): 235-265.

Kisekka, I., J.P. Aguilar, D. Rogers, J. Holman, D. O'Brian, and N. Klock. 2015. Assessing deficit irrigation strategies for corn using simulation. In: *2015 ASABE/IA Irrigation Symposium: Emerging Technologies for Sustainable Irrigation-A Tribute to the Career of Terry Howell, Sr. Conference Proceedings*. American Society of Agricultural and Biological Engineers, pp. 1-28.

Legates, D.R. and G.J. McCabe. 1999. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research* 35(1): 233-241.

Liu, H.L., J.Y. Yang, C.F. Drury, W.D. Reynolds, C.S. Tan, Y.L. Bai, P. He, J. Jin, and G. Hoogenboom. 2011. Using the DSSAT-CERES-Maize model to simulate crop yield and nitrogen cycling in fields under long-term continuous maize production. *Nutrient Cycling in Agroecosystems* 89(3): 313-328.

Luo, Q., M. Bange, D. Johnston, and M. Braunack. 2015. Cotton crop water use and water use efficiency in a changing climate. *Agriculture, Ecosystems & Environment* 202: 126-134.

Marek, G.W., P.H. Gowda, S.R. Evett, R.L. Baumhardt, D.K. Brauer, T.A. Howell, T.H. Marek, and R. Srinivasan. 2016a. Calibration and validation of the SWAT model for predicting daily ET over irrigated crops in the Texas High Plains using lysimetric data. *Transactions of the American Society of Agricultural and Biological Engineers* 59(2): 611-622.

Marek, G., P. Gowda, T. Marek, B. Auvermann, S. Evett, P. Colaizzi, and D. Brauer. 2016b. Estimating preseason irrigation losses by characterizing evaporation of effective precipitation under bare soil conditions using large weighing lysimeters. *Agricultural Water Management* 169: 115-128.

Marek, G.W., T.H. Marek, Q. Xue, P.H. Gowda, S.R. Evett, and D.K. Brauer. 2017. Simulating evapotranspiration (ET) and yield response of selected corn varieties under full and limited irrigation in the Texas High Plains using DSSAT-CERES-Maize. *Transactions of the American Society of Agricultural and Biological Engineers* 60(3): 837-846.

Mauget, S.A., P. Adhikari, G. Leiker, R.L. Baumhardt, K.R. Thorp, and S. Ale. 2017. Modeling the effects of management and elevation on West Texas dryland cotton production. *Agricultural and Forest Meteorology* 247: 385-398.

Modala, N.R., S. Ale, N. Rajan, K.R. Thorp, and C. Munster. 2015. Simulating the impacts of future climate variability and change on cotton production in the Texas Rolling Plains. In: *Beltwide Cotton Conferences.* San Antonio, TX, pp. 5-7.

Musick, J.T., F.B. Pringle, and J.D. Walker. 1988. Sprinkler and furrow irrigation trends: Texas High Plains. *Applied Engineering in Agriculture* 4(1): 46-52.

Nieswiadomy, M. 1985. The demand for irrigation water in the high plains of Texas, 1957-80. *American Journal of Agricultural Economics* 67(3): 619-626.

Ortiz, B.V., G. Hoogenboom, G. Vellidis, K. Boote, R.F. Davis, C. Perry, and others. 2009. Adapting the CROPGRO-Cotton model to simulate cotton biomass and yield under southern root-knot nematode parasitism. *Transactions of the American Society of Agricultural and Biological Engineers* 52(6): 2129-2140.

Parvin, D.W., S.W. Martin, F. Cooke, Jr., and B.B. Freeland, Jr. 2005. Effect of harvest season rainfall on cotton yield. *Journal of Cotton Science* 9(3): 1408-1417.

Pettigrew, W.T., W.R. Meredith, Jr., and others. 2009. Seed quality and planting date effects on cotton lint yield, yield components, and fiber quality. *Journal of Cotton Science* 13(2): 37-47.

Porter, C.H., J.W. Jones, S. Adiku, A.J. Gijsman, O. Gargiulo, and J.B. Naab. 2010. Modeling organic carbon and carbon-mediated soil processes in DSSAT v4.5. *Operations Research* 10(3): 247-278.

Porter, D., T. Marek, T. Howell, and L. New. 2005. *Texas High Plains Evapotranspiration Network (TXHPET) User Manual*. Available at: http://cotton.tamu.edu/Irrigation/TXHPETUserManual.pdf. Accessed September 19, 2017.

Reddy, K., P. Doma, L. Mearns, M. Boone, H. Hodges, A. Richardson, and V. Kakani. 2002. Simulating the impacts of climate change on cotton production in the Mississippi Delta. *Climate Research* 22: 271-281.

Rezzoug, W., B. Gabrielle, A. Suleiman, and K. Benabdeli. 2008. Application and evaluation of the DSSAT-Wheat in the Tiaret region of Algeria. *African Journal of Agricultural Research* 3(4): 284-296.

Ritchie, T. and S. Otter. 1985. Description and performance of CERES-Wheat: A user oriented wheat yield model. In: *ARS Wheat Yield Project*. ARS-28. National Technology Information Service, Springfield, VA, pp. 159-175.

Robertson, B., C. Bednarz, and C. Burmester. 2007. Growth and development – First 60 Days. Available at http://agrilife.org/lubbock/files/2011/10/cptvol13no22007.pdf. Accessed October 27, 2017.

Scanlon, B.R., R.W. Healy, and P.G. Cook. 2002. Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal* 10(1): 18-39.

Sophocleous, M. 2010. Review: Groundwater management practices, challenges, and innovations in the High Plains Aquifer, USA—Lessons and recommended actions. *Hydrogeology Journal* 18(3): 559-575.

Thorp, K.R., E.M. Barnes, D.J. Hunsaker, B.A. Kimball, J.W. White, V.J. Nazareth, and G. Hoogenboom. 2014. Evaluation of CSM-CROPGRO-Cotton for simulating effects of management and climate change on cotton growth and evapotranspiration in an arid environment. *Transactions of the American Society of Agricultural and Biological Engineers* 57(6): 1627-1642.

Thorp, K.R., K.C. DeJonge, A.L. Kaleita, W.D. Batchelor, and J.O. Paz. 2008. Methodology for the use of DSSAT models for precision agriculture decision support. *Computers and Electronics in Agriculture* 64(2): 276-285.

USDA. 2012. Texas agricultural statistics. USDA National Agricultural Statistics Service. Available at: https://www.nass.usda.gov/Statistics_by_State/Texas/Publications/Annual_Statistical_Bulletin/bull2009.pdf . Accessed September 19, 2017.

Wajid, A., A. Ahmad, M. Hussain, M.H. Rahman, T. Khaliq, M. Mubeen, F. Rasul, U. Bashir, M. Awais, J. Iqbal, and others. 2014. Modeling growth, development and seed cotton yield for varying nitrogen increments and planting dates using DSSAT. *Pakistan Journal of Agricultural Sciences* 51(3): 641-649.

Walter, I.A., R.G. Allen, R. Elliott, D. Itensfisu, P. Brown, M.E. Jensen, B. Mecham, T.A. Howell, R. Snyder, S. Echings, T. Spofford, M. Hattendrof, D. Martin, R.H. Cuenca, and J.L. Wright. 2005. The ASCE standardized reference evapotranspiration equation. Reston, Virginia.

Wilding, L.P. 1985. Spatial variability: Its documentation, accommodation, and implementation to soil surveys. In: *Soil Spatial Variability*, D.R. Nielson and J. Bouma (Eds.). Pudoc, Wageningen, Netherlands.

Willmott, C.J., S.G. Ackleson, R.E. Davis, J.J. Feddema, K.M. Klink, D.R. Legates, J. O'Donnell, and M. Rowe. 1985. Statistics for the evaluation and comparison of models. *Journal of Geophysical Research* 90(C5): 8995-9005.

Zamora, D.S., S. Jose, J.W. Jones, and W.P. Cropper. 2009. Modeling cotton production response to shading in a pecan alleycropping system using CROPGRO. *Agroforestry Systems* 76(2): 423-435.