SIMULATED EFFECTS OF WINTER WHEAT COVER CROP ON COTTON PRODUCTION SYSTEMS OF THE TEXAS ROLLING PLAINS

crop modeling
to optimize
water use
ASABE

P. Adhikari, N. Omani, S. Ale, P. B. DeLaune, K. R. Thorp,
E. M. Barnes, G. Hoogenboom

ABSTRACT. *Interest in cover crops has been increasing in the Texas Rolling Plains (TRP) region, mainly to improve soil health. However, there are concerns that cover crops could potentially reduce soil water and thereby affect the yield of subsequent cash crops. Previous field studies from this region have demonstrated mixed results, with some showing a reduction in cash crop yield due to cover crops and others indicating no significant impact of cover crops on subsequent cotton fiber yield. The objectives of this study were to (1) evaluate the CROPGRO-Cotton and CERES-Wheat modules within the cropping system model (CSM) of the Decision Support System for Agrotechnology Transfer (DSSAT) for the TRP region, and (2) use the evaluated model to assess the long-term effects of growing winter wheat as a cover crop on water balances and seed cotton yield under irrigated and dryland conditions. The two DSSAT crop modules were calibrated using measured data on soil water and crop yield from four treatments: (1) irrigated cotton without a cover crop (CwoC-I), (2) irrigated cotton with winter wheat as a cover crop (CwC-I), (3) dryland cotton without a cover crop (CwoC-D), and (4) dryland cotton with a winter wheat cover crop (CwC-D) at the Texas A&M AgriLife Research Station at Chillicothe from 2011 to 2015. The average percent error (PE) between the CSM-CROPGRO-Cotton simulated and measured seed cotton yield was -10.1% and -1.0% during the calibration and evaluation periods, respectively, and the percent root mean square error (%RMSE) was 11.9% during calibration and 27.6% during evaluation. For simulation of aboveground biomass by the CSM-CERES-Wheat model, the PE and %RMSE were 8.9% and 9.1%, respectively, during calibration and -0.9% and 21.8%, respectively, during evaluation. Results from the long-term (2001-2015) simulations indicated that there was no substantial reduction in average seed cotton yield and soil water due to growing winter wheat as a cover crop.*

Keywords. *CERES-Wheat, Cover crop, Crop simulation model, CROPGRO-Cotton, DSSAT, Seed cotton yield, Soil water.*

The Texas Rolling Plains (TRP) region is predominately made up of monoculture cropping systems, with cotton and wheat accounting for more than one million hectares. In recent times, there has been an increasing interest in cover crops in this region, mainly to build soil health, which is defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (NRCS, 2017). A cover crop is a transition crop between two production systems, and it has the potential to provide multiple benefits, such as preventing soil erosion, improving soil physical and biological properties, supplying nutrients, suppressing weeds, improving the availability of soil water, and breaking pest cycles. Many researchers have emphasized that cover crops increase soil organic matter, infiltration rate, and nitrogen fertilizer use efficiency (Bordovsky et al., 1999; Veenstra et al., 2007; Li et al., 2008). In contrast, several other researchers (Balkcom et al., 2007; Dabney et al., 2001) reported a potential disadvantage of reducing soil water for subsequent cash crops when growing cover crops.

Some of the field studies (Baughman et al., 2007; Dozier et al., 2008; Keeling et al., 1996) conducted in the TRP and the adjacent Texas High Plains (THP) regions have also reported a decrease in soil water due to introducing cover crops into traditional cropping systems. However, other recent field studies in the TRP region have indicated that cover crops have not affected soil water availability for the main crop. Various researchers (Baumhardt and Lascano, 1999; DeLaune et al., 2012; Lascano et al., 2015) found no significant impact of a wheat cover crop on subsequent cotton

---

Submitted for review in February 2017 as manuscript number NRES 12272; approved for publication as part of the "Crop Modeling and Decision Support for Optimizing Use of Limited Water" collection by the Natural Resources & Environmental Systems Community of ASABE in September 2017.

The authors are **Pradip Adhikari, ASABE Member,** Postdoctoral Fellow, Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, Oklahoma; **Nina Omani, ASABE Member,** Postdoctoral Research Associate, **Srinivasulu Ale, ASABE Member,** Associate Professor, and **Paul B. DeLaune,** Associate Professor, Texas A&M AgriLife Research, Vernon, Texas; **Kelly R. Thorp, ASABE Member,** Research Agricultural Engineer, USDA-ARS Arid Land Agricultural Research Center, Maricopa, Arizona; **Edward M. Barnes, ASABE Fellow,** Senior Director, Agricultural and Environmental Research, Cotton Incorporated, Cary, North Carolina; **Gerrit Hoogenboom, ASABE Member,** Professor, Department of Agricultural and Biological Engineering, University of Florida, Gainesville, Florida. **Corresponding author:** Srinivasulu Ale, Texas A&M AgriLife Research, P.O. Box 1658, 11708 Highway 70S, Vernon, TX 76385; phone: 940-552-9941, ext. 232; e-mail: sriniale@ag.tamu.edu; Srinivasulu.Ale@gmail.com.

Vol. 60(6): 2083-2096 2017 American Society of Agricultural and Biological Engineers ISSN 2151-0032 https://doi.org/10.13031/trans.12272

fiber yield in both dryland and irrigated systems. Sij et al. (2004) also found no significant difference in cotton fiber yield because of rye cover crop over a three-year period. Balkcom et al. (2007) noted that the impact of cover crops on soil water was dependent on rainfall distribution in relation to crop development.

Analysis of long-term water balances under cover crop-based cropping systems in comparison to traditional cotton monoculture systems will enable a better understanding of the impacts of cover crops on soil water availability for cotton and on seed cotton yield under varied weather conditions. The Decision Support System for Agrotechnology Transfer (DSSAT) cropping system model (CSM) is useful for this purpose. According to Jones et al. (2003), the DSSAT CSM is a suitable alternative for conducting long-term on-farm water management studies in areas where water availability is a major concern. Salmerón et al. (2014) used the DSSAT CSM to evaluate the impact of a cover crop-maize rotation on N leaching for a range of soil types and irrigation management practices in Spain. Modala et al. (2015) used the DSSAT CSM-CROPGRO-Cotton model to identify appropriate deficit-irrigation strategies for increasing water use efficiency in the TRP region. Recently, Adhikari et al. (2016) used the CSM-CROPGRO-Cotton model to simulate future (2041-2070) seed cotton yields in the THP region under increasing and constant atmospheric CO_2 concentration scenarios.

The DSSAT CSM-CROPSIM-CERES (Crop Estimation through Resource and Environment Synthesis)-Wheat model has also been used by many researchers (Lobell and Ortiz-Monasterio, 2006; Thorp et al., 2010) for evaluating various water management strategies for wheat in different geographic locations of the world. Recently, Attia et al. (2016) calibrated and evaluated the DSSAT-CERES-Wheat model for the THP region and simulated winter wheat responses to irrigation management. They reported that the calibrated model responded very well to different levels of irrigation, ranging from dryland to full irrigation, and simulated wheat yield (aboveground biomass) accurately. The DSSAT CSM has also been used by various other researchers (He et al., 2013; Timsina et al., 2008; Panda et al., 2003) to develop irrigation scheduling tools for wheat. All of the above-mentioned researchers adequately tested their models against field measurements before addressing the research questions related to crop and water management. Almost all of these studies used only one of the crop modules available in the DSSAT-CSM model and simulated the effects of different crop management practices and climate variability on various processes during the main (summer) cropping season only. They did not simulate soil-related processes in fallow periods between two summer crop seasons, and initial conditions were reset prior to each crop season. In this study, we used two different crop modules (CROPGRO-Cotton and CERES-Wheat) sequentially over a continuous four-year period and simulated daily soil-related processes continuously by including fallow periods between cotton and wheat cover crop seasons.

Winter wheat is one of the major small-grain crops typically planted for grain or forage in the TRP region. The TRP region accounts for ~29% of the winter wheat area in Texas (USDA, 2012). In recent times, along with other crops, winter wheat has been increasingly grown as a cover crop in TRP cotton production systems. Some of the other cover crops recommended for the southern U.S. are rye, oats, hairy vetch, and crimson clover (Clark, 2007). Winter wheat was selected as a cover crop for this study because it is readily grown and available in the TRP region. Depending on weather suitability, winter wheat also offers flexibility for growth as a cover crop, forage crop, or cash crop for grain, making it a popular choice to help growers minimize risk. In addition, winter wheat can withstand extreme winter weather conditions, and it provides a good option to control wind erosion during early spring, when the TRP region commonly experiences high wind speeds. Considering the growing interest in incorporating winter wheat cover crop into cotton production systems in the TRP, research must address the potential impacts to traditional cropping systems. Therefore, the objectives of the study were to: (1) evaluate the DSSAT CSM CROPGRO-Cotton and CERES-Wheat modules for the TRP region using measured data from cover crop (winter wheat and cotton) experiments at the Texas A&M AgriLife Research Station at Chillicothe, and (2) assess the long-term effects of growing winter wheat as a cover crop on water balances and seed cotton yield.

MATERIALS AND METHODS

STUDY AREA: THE TEXAS ROLLING PLAINS

The TRP region consists of 22 counties in north-central Texas, and it borders Oklahoma to the north (fig. 1). The annual precipitation in the TRP region ranges from 460 mm in the west to 760 mm in the east, with most occurring between May and September. Major crops grown in the TRP region are cotton, winter wheat, and sorghum, and the major source of irrigation water is the Seymour Aquifer. Almost 90% of the groundwater pumped from this aquifer is used for irrigation, with the remainder used primarily for municipal supply (http://www.twdb.texas.gov). The most common method of irrigation in the TRP region is center-pivot sprinkler irrigation. In this study, measured data from cover crop experiments at the Texas A&M AgriLife Research Station at

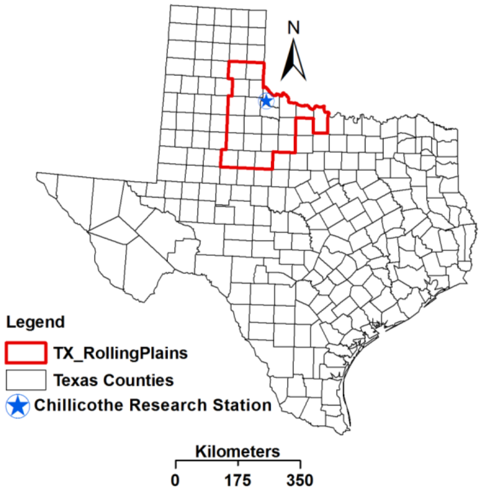

Figure 1. Chillicothe Research Station in the Texas Rolling Plains.

Chillicothe in the TRP were used to calibrate and evaluate the CROPGRO-Cotton and CERES-Wheat modules in the DSSAT CSM. The dominant soil types at the Chillicothe research station are Grandfield fine sandy loam, Abilene clay loam, Tipton loam, and Motely loam.

DSSAT CROPPING SYSTEM MODEL (CSM)

The DSSAT platform integrates different crop models and a detailed database management system consisting of soil characteristics, weather parameters, and management practices with various application programs (Hoogenboom et al., 2010). The DSSAT 4.6.0.038 version was used in the current study. It brings together 42 individually developed crop modules in a single platform (Hoogenboom et al., 2015). The CSM-CROPGRO-Cotton and CSM-CROPSIM-CERES-Wheat modules were used in this study. Based on the weather, soils, crop management, and cultivar-related input data, the CSM-CROPGRO-Cotton model simulates cotton growth and seed cotton yield as well as soil water, C, and N processes over time. In addition, the CSM-CROPGRO-Cotton model estimates the onset dates of various crop development stages based on photothermal unit accumulation from planting to harvest (emergence; first leaf, flower, seed and crack boll; and 90% open boll), and the model simulates flower and fruit numbers. Similarly, the CSM-CROPSIM-CERES-Wheat model simulates crop growth and development of wheat in response to weather and management factors (Ritchie and Otter, 1985). Wheat development proceeds through nine growth stages based on photothermal unit accumulation from planting to harvest, and leaf numbers are computed during vegetative growth stages. The CERES-Wheat module uses carbon, nitrogen, and water balance principles to simulate the processes that occur during the growth and development of wheat plants within an agricultural system.

Both the CSM-CROPGRO-Cotton and CSM-CROPSIM-CERES-Wheat modules require various crop management, environment, and cultivar-related information as inputs (Hunt et al., 2001). Important crop management parameters include the method of irrigation, irrigation dates and amounts, fertilizer application method, fertilizer amount and application dates, tillage type, tillage depth and dates, planting date and method, seedling placement depth, plant population, row spacing, and harvest method and date. Weather parameters required as inputs are daily maximum and minimum air temperature, incoming daily solar irradiance, and precipitation, while dew point temperature and wind speed are optional. Cultivar information is incorporated in three files for the cultivar (COGRO046.CUL for cotton, and WHCER046.CUL for wheat), ecotype (COGRO046.ECO and WHCER046.ECO), and species (COGRO046.SPE and WHCER046.SPE).

In the DSSAT CSM, the seasonal and annual water balances are calculated using the following relationship:

$$\Delta S = I + P - D - R - T - E_{soil} - E_{mulch} \qquad (1)$$

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), E_{soil} is soil evaporation (mm), and E_{mulch} is evaporation from the mulch surface (mm).

MODEL INPUTS

Weather Data

Daily weather data for this study, such as the maximum and minimum air temperature, incoming daily solar irradiance, precipitation, dew point temperature, and wind speed, were obtained from the Texas High Plains Evapotranspiration Network (TXHPET) weather station at the Chillicothe Research Station for the period from 2000 to 2015 (Porter et al., 2005). Missing weather data for the Chillicothe Research Station were filled in using measured data from nearby weather stations located at Vernon/Lockett, Texas (TXHPET), Odell, Texas (operated by the West Texas Mesonet), and Altus, Oklahoma (operated by the Oklahoma Mesonet).

Crop Management Data

Crop management data for both cotton and winter wheat (grown as a cover crop) were obtained from the cover crop experiments at the Chillicothe Research Station (fig. 1) during the period from 2011 to 2015. These experiments consisted of cotton production systems under four treatments: (1) irrigated cotton without a cover crop (CwoC-I), (2) irrigated cotton with winter wheat as a cover crop (CwC-I), (3) dryland cotton without a cover crop (CwoC-D), and (4) dryland cotton with a winter wheat cover crop (CwC-D). Four replications of each treatment were established. Cotton seeds were planted using a mechanical planter at 1 m row spacing. Plots within the irrigated and dryland systems were 18 m × 8 m and 12 m × 8 m in size, respectively. A mechanical harvester was used to harvest cotton, and harvested subsamples were ginned to obtained fiber yields. Irrigation water for the irrigated treatments was supplied through a center-pivot system with a goal to achieve 85% ET replacement based on data obtained from the TXHPET network. The details of tillage, crop, and irrigation management practices adopted for cotton and winter wheat at Chillicothe are outlined in table 1.

Soil Data

The DSSAT CSM requires various soil parameters as inputs, including sand, silt, and clay contents, bulk density, drained upper limit (DUL), lower limit (LL), slope, albedo, color, drainage coefficient, saturated water content, hydraulic conductivity, organic C content, and total soil N. The dominant soil type in both irrigated and dryland fields at Chillicothe is Grandfield fine sandy loam (fine-loamy, mixed, superactive, thermic Typic Haplustalfs), which is characterized as a well-drained soil that is suitable for cotton cultivation (USDA, 2008). Soil water was measured in each plot during two-week intervals using neutron probes at 0-20, 20-40, 40-60, 60-80, and 80-140 cm depths. In addition, soil samples were collected from both irrigated and dryland experimental plots at 0-15, 15-30, 30-45, 45-60, 60-75, 75-90, 90-105, and 105-120 cm depth intervals. All soil samples were air-dried, ground, and sieved with a 2 mm sieve in the Texas A&M AgriLife Research Geospatial Hydrology laboratory at Vernon. Soil samples were then analyzed for soil texture, organic matter (OM), soil organic carbon (SOC),

Table 1. Management practices for cotton and wheat at Chillicothe Research Station during the growing seasons in different years.

		Growing Season			
Crop	Management Practice	2012	2013	2014	2015
Cotton[a]	Planting date	8 June	3 June	20 May	23 June
	Harvest date	24 Oct.	26 Oct.	24 Oct.	24 Oct.
	Seed rate (seed m^{-2})	13	13	13	13
	Irrigation start date	12 June	4 June	7 July	8 July
	Irrigation end date	1 Sept.	6 Sept.	28 Aug.	6 Sept.
	Annual irrigation amount (mm)	317	282	150	216
	Number of irrigations	10	16	9	12
	Type of fertilizer	28-0-0	28-0-0	28-0-0	28-0-0
	Elemental N (kg ha^{-1})[b]	45	54	45	54
	Tillage	No-till	No-till	No-till	No-till
Wheat		2011-2012	2012-2013	2013-2014	2014-2015
	Planting date	31 Oct. 2011	28 Oct. 2012	31 Oct. 2013	1 Nov. 2014
	Harvest/termination date	30 Apr. 2012	24 Apr. 2013	20 Apr. 2014	30 Apr. 2015
	Seed rate (seed m^{-2})	102	102	102	102
	Irrigation (mm)	-	-	-	-
	Tillage	No-till	No-till	No-till	No-till

[a] Similar management practices were adopted for dryland cotton except that fertilizer was not applied.

[b] For irrigated cotton, 30 to 60 kg N ha^{-1} was additionally input to the system to account for about 20 mg L^{-1} of NO_3-N available in the irrigation water (DeLaune and Trostle, 2012).

Table 2. Soil related input parameters used in the DSSAT cropping system model.[a]

Depth (cm)	Clay (%)	Silt (%)	SOC (%)	TN (%)	pH	CEC (cmol kg^{-1})	BD (g cm^{-3})	LL (cm^3 cm^{-3})	DUL (cm^3 cm^{-3})	SSAT (cm^3 cm^{-3})	SSKS (cm h^{-1})	SRGF
0-5	9	23	0.43	0.10	7.1	11	1.53	0.04	0.13	0.398	2.59	1.000
5-15	9	23	0.43	0.10	7.1	11	1.53	0.04	0.15	0.398	2.59	1.000
15-20	11	24	0.41	0.10	7.0	11	1.54	0.08	0.15	0.394	2.59	1.000
20-40	19	18	0.52	0.07	7.2	16	1.53	0.14	0.19	0.397	2.59	0.549
40-60	25	23	0.46	0.07	7.2	17	1.50	0.14	0.19	0.408	2.59	0.368
60-80	27	25	0.43	0.05	7.3	21	1.50	0.05	0.14	0.409	2.59	0.247
80-100	25	28	0.39	0.04	7.6	27	1.50	0.07	0.16	0.407	1.32	0.165
100-120	23	28	0.66	0.04	7.9	29	1.50	0.07	0.16	0.406	1.32	0.131
120-140	27	28	0.72	0.04	8.2	29	1.50	0.07	0.16	0.406	1.32	0.074
140-170	27	28	0.72	0.04	8.2	30	1.50	0.07	0.16	0.406	1.32	0.050
170-200	27	28	0.72	0.04	8.2	30	1.50	0.07	0.16	0.406	1.32	0.020

[a] SOC = soil organic carbon, TN = total nitrogen concentration, CEC = cation exchange capacity, BD = bulk density, LL= lower limit, DUL = drained upper limit, SSAT= soil water at saturation, SSKS = saturated hydraulic conductivity, and SRGF = soil root growth factor

$pH_{1:1}$, nitrate, cation exchange capacity (CEC), sodium, phosphate, and calcium in the Ward Laboratory at Kearney, Nebraska, following standard procedures (table 2). Other soil parameters, such as drained upper limit (DUL), lower limit (LL), soil water at saturation (SSAT), saturated hydraulic conductivity (SSKS), and bulk density (BD), were estimated using the SBuild soil data tool in DSSAT (Uryasev et al., 2004). The exponential decay function provided within DSSAT was used to estimate soil root growth factor (SRGF).

MODEL CALIBRATION AND EVALUATION

Model calibration generally involves systematic adjustment of model parameters until an acceptable agreement between measured experimental data and simulated model output is achieved, whereas evaluation is the process of determining the degree of accuracy of the calibrated model with real-world observations. In this study, four DSSAT sequential projects (one for each treatment) were created. The CSM-CROPGRO-Cotton and CSM-CROPSIM-CERES-Wheat modules within the DSSAT CSM were then calibrated and evaluated using the measured data from cover crop experiments at the Chillicothe Research Station. Measured soil water data from 0-20, 20-40, 40-60, 60-80, and 80-140 cm depth profiles over the period from day of year 3 (3 DOY) 2013 to 298 DOY 2013 were used for the DSSAT CSM soil water calibration, and data from 315 DOY 2013 to 255 DOY 2015 were used for evaluation. The measured seed cotton yield data from the CwC-I, CwoC-I, CwC-D, and CwoC-D treatments during the 2013 growing season were used for the CSM-CROPGRO-Cotton model crop yield calibration, and measured seed cotton yield data from the 2014 and 2015 growing seasons were used for evaluation. For CSM-CROPSIM-CERES-Wheat, measured aboveground biomass data for winter wheat from the CwC-D treatment during the 2011-2012 growing season (i.e., wheat planted in fall 2011 and harvested/terminated in spring 2012) and from the CwC-I and CwC-D treatments during the 2012-2013 growing season were used to calibrate the model, and data from the CwC-I and CwC-D treatments during the 2013-2014 and 2014-2015 growing seasons were used to evaluate the model. In this experiment, irrigated cotton was not planted, and the dryland cotton crop failed in the 2012 growing season; hence, observed data from that season were not available for model calibration.

As the DSSAT database does not contain the DP1219 cotton and TAM112 wheat cultivars that were used in the Chillicothe experiments, we added them as new cultivars in the cotton and wheat cultivar files, respectively, and populated their parameters based on the closest available varieties in the model database. We then set up the upper and lower bounds for important cultivar and ecotype parameters that govern the crop growth and development, crop phenology, and crop yield for cotton and wheat based on the calibrated values included for other cultivars in the DSSAT database and calibrated values reported for the TRP and THP regions in published studies. These important parameters were adjusted manually during the model calibration to improve the model simulation. The effects of adjusting each sensitive parameter in the cotton and wheat cultivar and ecotype files on model performance were studied by comparing simulated and measured soil water, seed cotton yield, and aboveground wheat biomass. The model calibration was carried out in three steps. Initially, simulated daily soil water content in the 0-20, 20-40, 40-60, 60-80 and 80-140 cm depth profiles was compared with the measured soil water content. Second, the simulated onset dates of various cotton and wheat phenological stages were compared with typical dates in the study area. Finally, the simulated and measured seed cotton yield and aboveground biomass of wheat were compared.

The performance of the crop modules during calibration and evaluation was assessed following the procedure suggested by Yang et al. (2014). Four statistical parameters, including the coefficient of determination (r^2) (Legates and McCabe, 1999), percent root mean squared error (%RMSE, which is the RMSE divided by the mean of measured values, expressed as a percentage), index of agreement (d) (Willmott et al., 1985), and percent error (PE), were used to test the model performance. The r^2 ranges between 0 and 1, with 0 and 1 indicating “no fit” and “perfect fit”, respectively, between the simulated and measured values. The %RMSE varies between 0 and ∞, and values closer to 0 indicate better agreement between the simulated and measured values. The d value ranges between 0 (no agreement) and 1 (perfect fit). The PE ranges from -100 to ∞, and smaller absolute PE values closer to 0 indicate better agreement. We aimed to maximize r^2 during soil moisture calibration and minimize PE during yield/biomass calibration, while making sure that the remaining performance statistics were within the acceptable ranges.

LONG-TERM WATER BALANCES AND SEED COTTON YIELD

The calibrated DSSAT CSM was used to assess the effects of growing winter wheat as a cover crop on annual water balances and seed cotton yield sequentially over a long-term weather record. Simulations for both dryland and irrigated treatments were run over the period from 2000 to 2015, and the results for the year 2000 were excluded from the analysis by considering it as the model warm-up period (Daggupati et al., 2015). The auto-irrigation tool in the DSSAT CSM was used for estimating irrigation requirements for cotton over the growing season under the CwoC-I treatment. Irrigation was triggered when soil water was depleted to 50% of available soil water, and irrigation water was applied until the soil profile was filled to field capacity. For accurate comparison of the effects of cover crops, the same amount of irrigation water that was estimated for cotton under the CwoC-I treatment, using the auto-irrigation tool, was applied on respective dates for cotton in the CwC-I treatment. Additionally, auto-irrigation was implemented for the CwC-I treatment to verify if the negative effects, if any, of cover crops on seed cotton yield can be overcome by applying more irrigation water.

RESULTS AND DISCUSSION

CALIBRATION AND EVALUATION

The cotton and winter wheat genetic coefficients that were adjusted during model calibration are presented in tables 3 and 4, respectively. A total of 17 cultivar and ecotype parameters were adjusted during the CSM-CROPGRO-Cotton model calibration (table 3). Photothermal time between plant emergence and flower appearance (EM-FL), which was important for calculating the onset of flowering, was tested between 34 and 52 and adjusted to 48. Photothermal duration between first flower and first pod (FL-SH), which was important to simulate the timing of first boll, was adjusted to 4, and photothermal time between first flower and end of leaf expansion (FL-LF) was adjusted to 50 days. Similarly, other sensitive parameters that affect the photosynthesis rate, transpiration, and assimilation of carbon in

Table 3. Genetic coefficients and initial conditions adjusted during calibration of the CSM CROPGRO-Cotton module.

		Tested Range	Calibrated Value
Cultivar parameters			
EM-FL	Time between plant emergence and flower appearance (photothermal days)	34-52	48
FL-SH	Time between first flower and first pod (photothermal days)	1-12	4
FL-SD	Time between first flower and first seed (photothermal days)	4-18	8
SD-PM	Time between first seed and physiological maturity (photothermal days)	40-50	40
FL-LF	Time between first flower and end of leaf expansion (photothermal days)	45-75	50
LFMAX	Maximum leaf photosynthesis rate at 30°C, 350 ppm CO_2, and high light (mg CO_2 m^{-2} s^{-1})	0.7-1.4	1.1
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	160-180	170
SIZLF	Maximum size of full leaf (three leaflets) (cm^2)	250-320	300
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.7-0.9	0.8
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	22-40	35
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	8-14	12
THRSH	Threshing percentage; the maximum ratio of (seed / (seed + shell)) at maturity	68-72	70
Ecotype parameters			
PL-EM	Time between planting and emergence (thermal days)	2-7	4
EM-V1	Time required from emergence to first true leaf (thermal days)	3-5	4
RWDTH	Relative width of the ecotype in comparison to the standard width per node	0.8-1.3	1.0
RHGHT	Relative height of the ecotype in comparison to the standard height per node	0.8-1.0	0.9
FL-VS	Time from first flower to last leaf on main stem (photothermal days)	30-75	40
Initial conditions			
	Soil water (cm^3 cm^{-3})	0.10-0.33	0.28 (irrigated) 0.14 (dryland)
	Nitrate (μg g^{-1})	0.5-25	2.5 to 3.0

the plant, including the maximum leaf photosynthesis rate (LFMAX), specific leaf area (SLAVR), and maximum size of full leaf (SIZLF), were adjusted to 1.1 mg CO_2 m^{-2} s^{-2}, 170 cm^2 g^{-1}, and 300 cm^{-2}, respectively (table 3). These calibrated values for the CSM-CROPGRO-Cotton model calibration were comparable to the values reported by Modala et al. (2015) for the TRP region and by Adhikari et al. (2016) for the nearby THP region.

Ecotype parameters adjusted during the CSM-CROPGRO-Cotton model calibration were relative width of the ecotype in comparison to standard width per node (RWDTH), relative height of the ecotype in comparison to standard height per node (RHGHT), and photothermal time from first flower to last leaf on main stem (FL-VS), which were important for correctly simulating canopy width, canopy height, and cessation of the stem elongation, respectively (table 3).

Eleven winter wheat cultivar and ecotype genetic coefficients were adjusted during calibration of the CSM-CERES-Wheat model (table 4). The adjusted parameters that control winter wheat growth and development were the number of thermal units required to complete the P1 stage (P1), a parameter that controls the rate of development in relation to photoperiod in the P1 stage to improve simulation of Zadoks scale (P1D), number of optimum days required to complete vernalization (P1V), duration of phase from double ridges to end of leaf growth (P2), duration of phase from the end of leaf growth to end of spike growth (P3), and interval between successive leaf tip appearances (PHINT). After achieving a satisfactory calibration of wheat development, wheat biomass growth parameters, such as conversion rate from photosynthetically active radiation to dry matter before the end of leaf growth (PARUV) and conversion rate from photosynthetically active radiation to dry matter ratio after the end of leaf growth (PARUR), were adjusted. Finally, parameters that influence wheat yield, such as kernel number per unit canopy weight at anthesis (G1), standard kernel size under optimum conditions (G2), and standard non-stressed dry weight of a single tiller at maturity (G3), were adjusted. The calibrated values of P1, P1D, and P1V in this study were 400, 68, and 10, respectively (table 4). Although the calibrated value of P1V in this study matched with that reported in a recent study by Attia et al. (2016) for the nearby THP region, their calibrated values for P1 (420) and P1D (80) were higher. These small differences were probably due to the differences in weather parameters, planting dates, as well as cultivars.

Simulated soil water in different soil depth profiles matched reasonably well with measured soil water during the calibration period for the CwoC-I (fig. 2), CwC-I (fig. 3), CwoC-D (fig. 4), and CwC-D (fig. 5) treatments, as indicated by satisfactory performance statistics, e.g., r^2 varied between 0.66 and 0.82 (median = 0.75) for dryland treatments and between 0.57 and 0.89 (median = 0.70) for irrigated treatments. In general, the agreement between simulated and measured soil water was better for deeper soil depth profiles (%RMSE ranged from 4% to 32.9%) compared to the 0-20 cm soil layer (%RMSE ranged from 72.4% to 101%) during the calibration period. The model performance during the evaluation period was reduced, as indicated by lower performance statistics (r^2 varied between 0.22 and 0.65 for dryland treatments and between 0.34 and 0.81 for irrigated treatments). Once again, the agreement was better for deeper soil depth profiles (%RMSE ranged from 7.6% to 34.5%) compared to the 0-20 cm soil layer (%RMSE ranged from 33.4% to 43.7%). However, the differences in performance statistics between the 0-20 cm soil profile and deeper soil profiles was reduced substantially during the evaluation period when compared to the calibration period. One of the reasons for poor agreement in the case of the 0-20 cm soil profile was several unrealistically low (close to zero) measured soil water contents during the cotton harvest period, which might have resulted from measurement or instrument calibration errors. A potential reason for poor prediction during the evaluation period when compared to the calibration period could be the evaluation of the model over the relatively wet years of 2014 and 2015 when compared to the normal calibration year of 2013. Overall, based on visual assessment of the simulated versus observed soil water plots (figs. 2 through 5) and the performance statistics achieved for all soil profiles, the soil water calibration can be considered satisfactory.

The simulated onset dates of various phenological stages, such as emergence and anthesis, by the CROPGRO-Cotton and CERES-Wheat modules were within the ranges observed in the TRP region during the model calibration and evaluation (tables 5 and 6). While the observed data on cotton phenological stages were obtained from a published report (Robertson et al., 2007), the observed data for winter wheat were obtained from field experiments at Chillicothe,

Table 4. Genetic coefficients adjusted during calibration of the CSM CERES-Wheat module.

		Tested Range	Calibrated Value
Crop development parameters			
P1	Duration of phase from emergence to double ridges (°C d)	350-420	400
P1D	Percentage reduction in development rate in a photoperiod 10 h shorter than the threshold	40-70	68
P1V	Days at optimum vernalizing temperature required to complete vernalization	6-13	10
P2	Duration of phase from double ridges to end of leaf growth (°C d)	250-300	285
P3	Duration of phase from the end of leaf growth to the end of spike growth (°C d)	150-210	190
PHINT	Interval between successive leaf tip appearances (°C d)	20-95	30
Crop growth parameters (PAR = photosynthetically active radiation)			
PARUV	Conversion rate from PAR to dry matter before the end of leaf growth (g MJ^{-1})	1.2-2	1.5
PARUR	Conversion rate from PAR to dry matter ratio after the end of leaf growth (g MJ^{-1})	1.2-2	1.5
Crop yield parameters			
G1	Kernel number per unit canopy weight at anthesis (kernels g^{-1})	25-33	30
G2	Standard kernel size under optimum conditions (mg)	25-38	30
G3	Standard non-stressed dry weight of a single tiller at maturity (g)	0.7-1.10	1

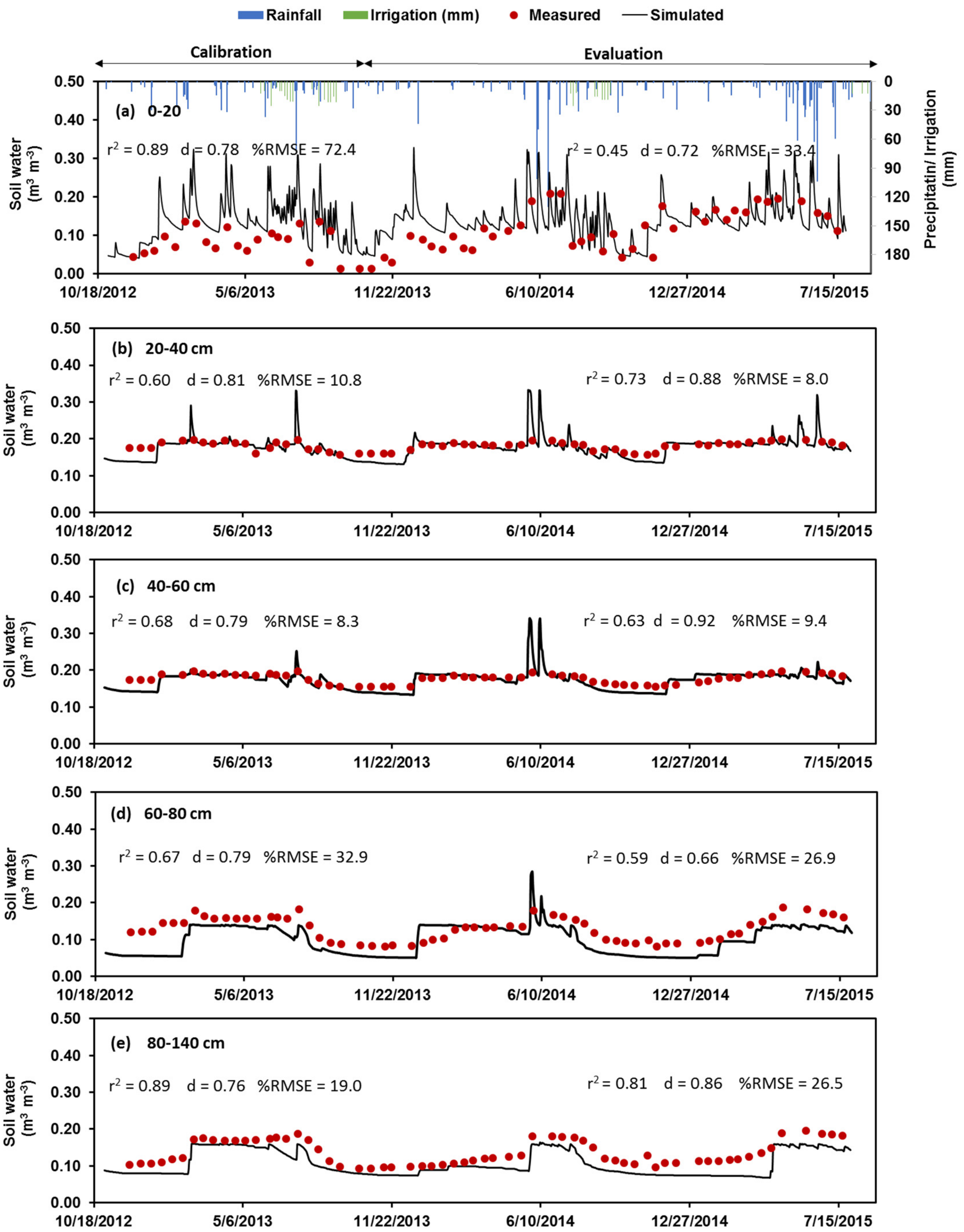

Figure 2. Comparison of simulated and measured soil water content in different soil depth profiles for the CwoC-I treatment (irrigated cotton without cover crop) during the calibration and evaluation periods.

except for a few occasions. Although the simulated cotton physiological maturity durations varied among various years and treatments, they were mostly within the observed ranges for the TRP region (table 5). Differences in maturity duration might have been due to differences in photothermal duration, precipitation, and other weather-related parameters during the growing seasons. Winter wheat was terminated before maturity in these experiments; hence, this phenological stage could not be compared (table 6).

Simulated seed cotton yield matched well with the measured data from the CwoC-I, CwC-I, CwoC-D, and CwC-D treatments during the calibration and evaluation periods, as indicated by the model performance statistics (r^2, %RMSE, d, and PE) achieved during the model calibration and evaluation (table 7). The PE for seed cotton yield simulation ranged between -12% and -7.1% during the calibration period and between -36.7% and 38.9% during the evaluation period (table 7). The average PE between the simulated and measured seed cotton yield was -10.1% and -1% during the calibration and evaluation periods, respectively. The d value during the calibration and evaluation periods was 0.99 and 0.95, respectively. In general, the CSM-CROPGRO-Cotton model predicted seed cotton yield better under dryland conditions (CwoC-D and CwC-D) when compared to irrigated

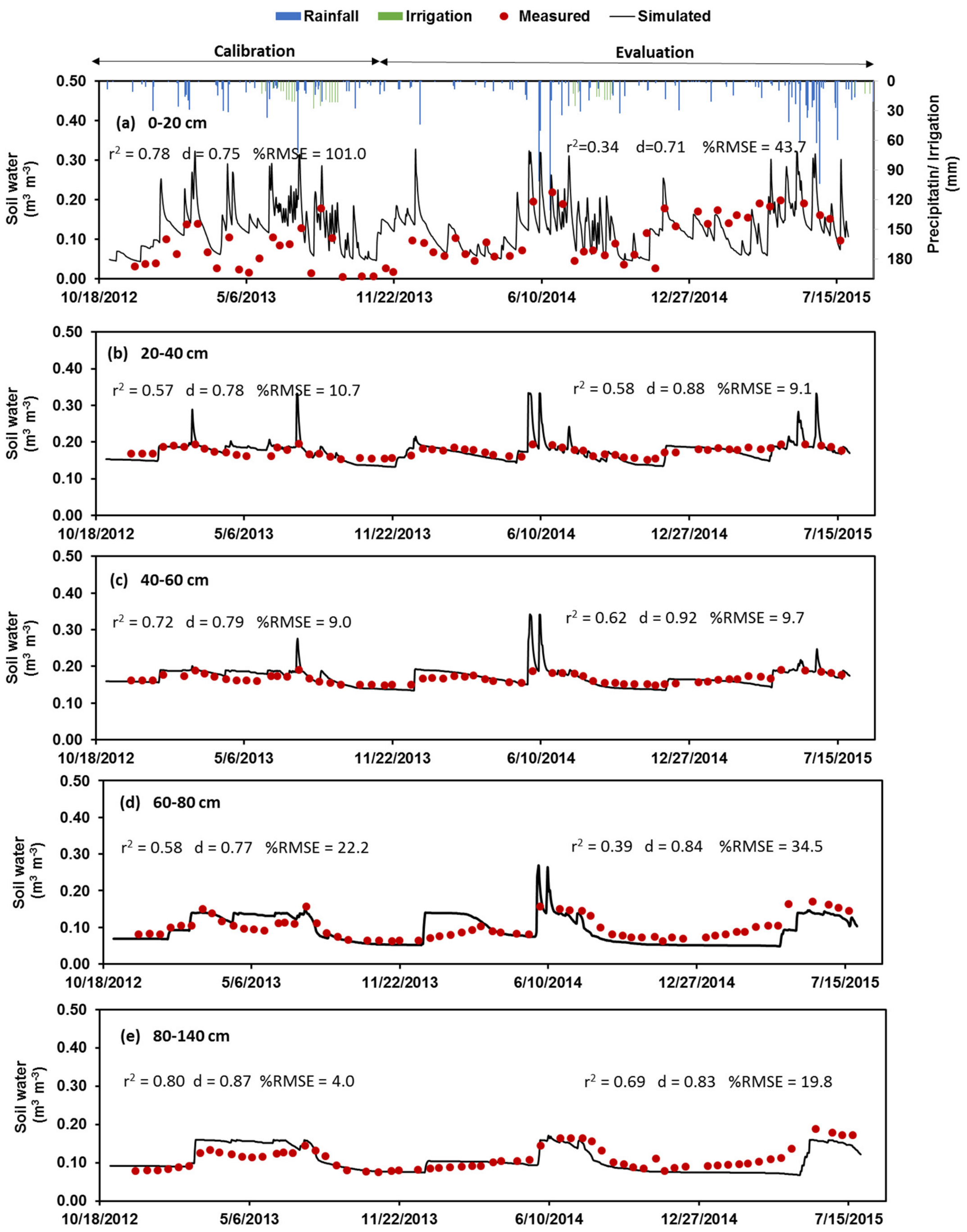

Figure 3. Comparison of simulated and measured soil water content in different soil depth profiles for the CwC-I treatment (irrigated cotton with cover crop) during the model calibration and evaluation periods.

conditions (CwC-I and CwoC-I) in this study. Overall, except for three cases, the PE for seed cotton yield prediction was within ±14%.

The aboveground wheat biomass simulated by the CSM-CERES-Wheat model also showed good agreement with the measured data under both irrigated and dryland conditions during the model calibration and evaluation periods (table 8). The PE for winter wheat aboveground biomass prediction ranged between 6.4% and 11% (with an average of 8.9%) during model calibration and between -32% and 30.4% (with an average of -0.9%) during evaluation. The %RMSE and r^2 were 9.1% and 0.99, respectively, during model calibration and 21.8% and 0.72, respectively, during evaluation.

EFFECT OF WINTER WHEAT COVER CROP ON WATER BALANCE COMPONENTS

The long-term simulated water balance components, including transpiration, runoff, soil evaporation, mulch evaporation, drainage, and change in soil water, under dryland and irrigated cotton systems with and without cover crops are presented in figures 6 and 7. The simulated average (2001-2015) annual change in soil water was -4.8 mm (ranged from -118.0 to 63.7 mm) and -0.8 mm (ranged from -114 to 65.2 mm) for the CwC-D and CwoC-D treatments,

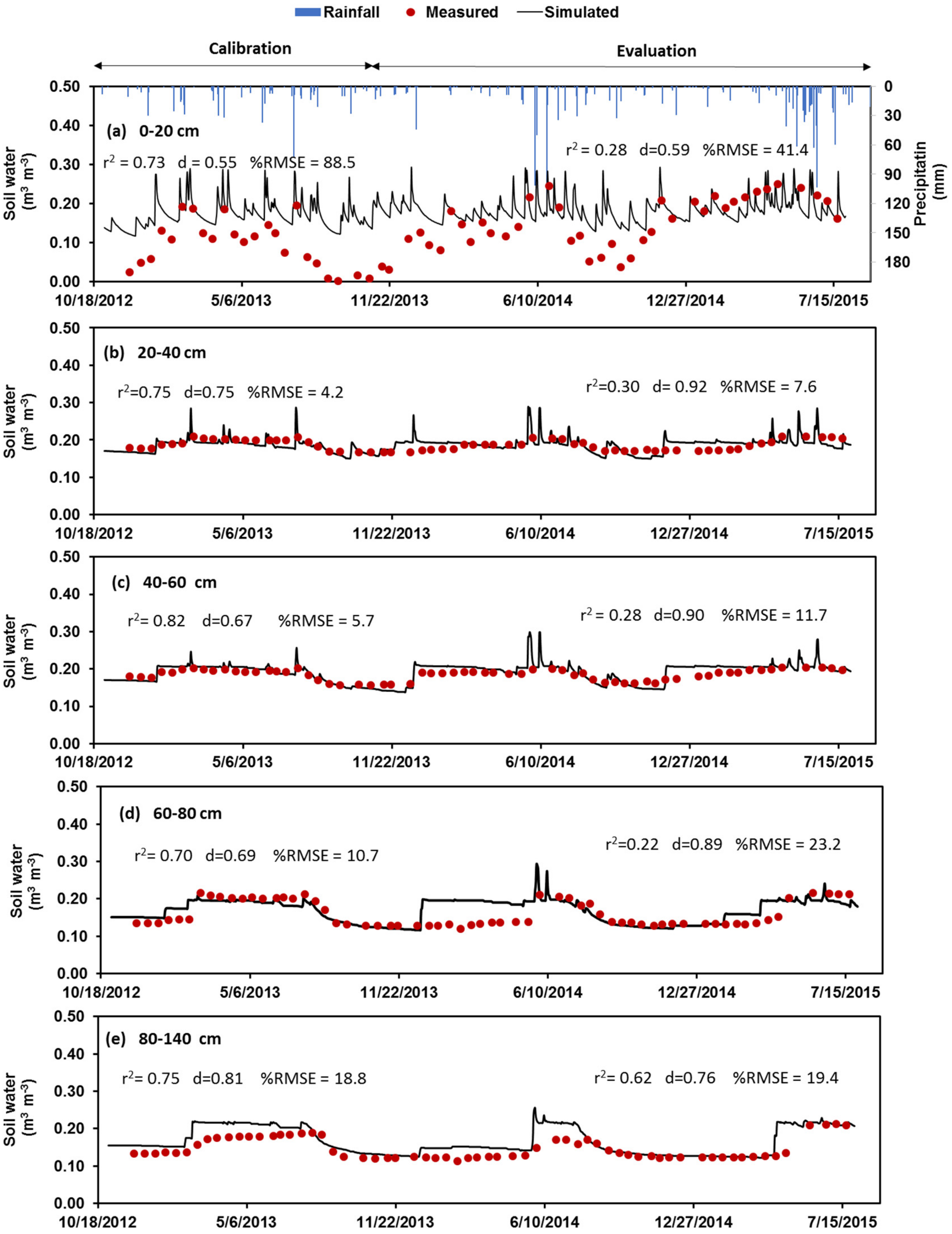

Figure 4. Comparison of simulated and measured soil water content in different soil depth profiles for the CwoC-D treatment (dryland cotton without cover crop) during the model calibration and evaluation periods.

respectively, indicating no distinguishable effect of winter wheat on soil water availability for succeeding cotton crops (fig. 6). However, the differences in other water balance components, such as mulch evaporation, soil evaporation, and transpiration, were substantial between the CwC-D and CwoC-D treatments. While mulch evaporation and transpiration were higher in the CwC-D treatment, soil evaporation was higher in the CwoC-D treatment. For the cover crop treatment, the presence of surface residue reduced the water evaporation from soil surfaces. There were no significant differences in drainage and runoff between the CwC-D and CwoC-D treatments.

In the irrigated system, there was no substantial difference in the simulated average (2001-2015) annual change in soil water between the CwC-I (0.3 mm) and CwoC-I (3.9 mm) treatments (fig. 7). Excluding two outliers, interestingly, the interannual variability in the change in soil water was less for the cover crop treatment compared to the no-cover-crop treatment. As expected, higher transpiration was simulated for the CwC-I treatment compared to the CwoC-I

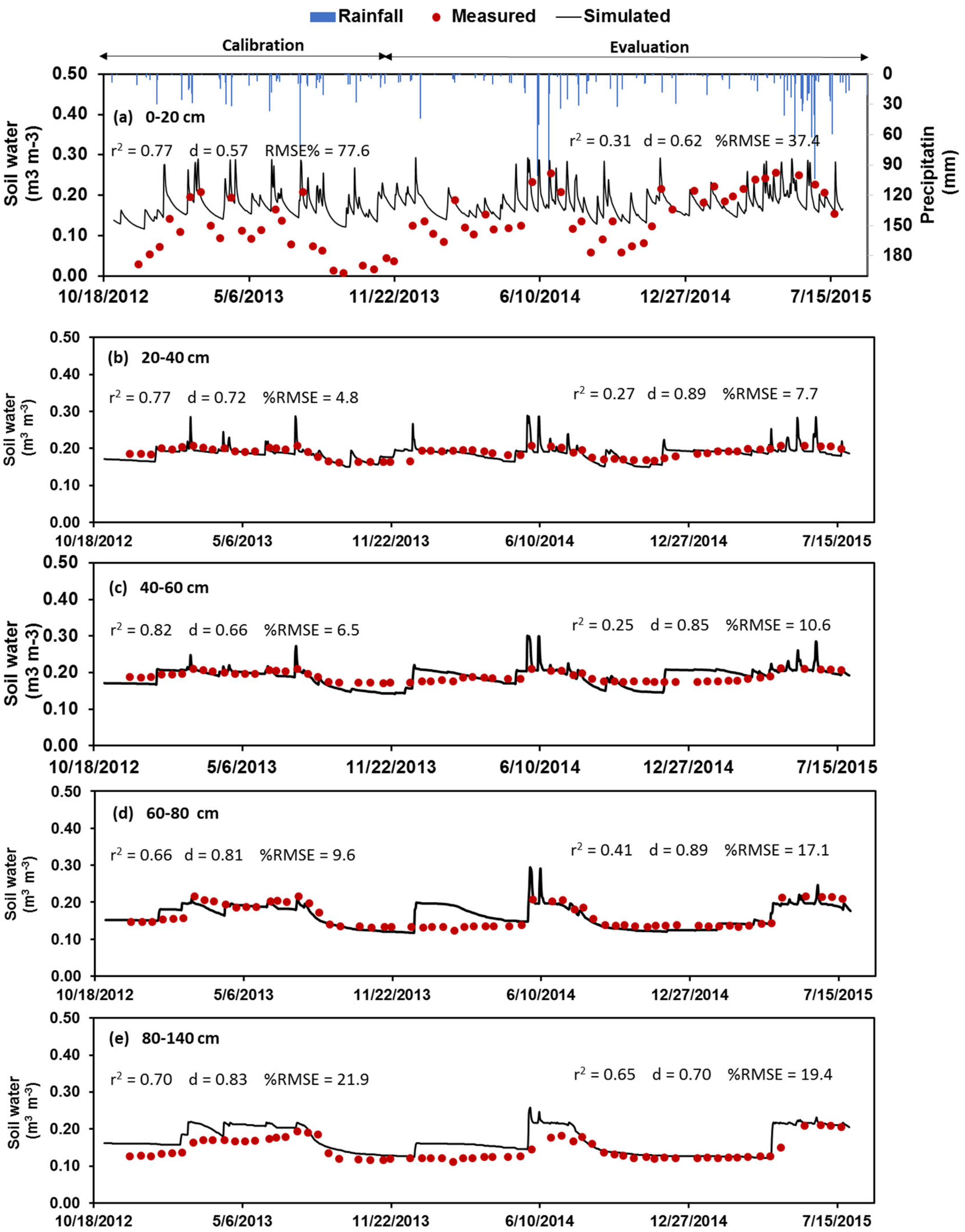

Figure 5. Comparison of simulated and measured soil water content in different soil depth profiles for the CwC-D treatment (dryland cotton with cover crop) during the model calibration and evaluation periods.

treatment, which was due to additional transpiration from the cover crop. Distinguishably lower soil evaporation was simulated for the CwC-I treatment compared to the CwoC-I treatment due to surface cover from wheat during winter. Previous studies (Mitchell et al., 2015; Alcántara et al., 2011) reported mixed results on the effects of cover crops on soil water. In a study conducted in an irrigated field in the Central Valley of California, Mitchell et al. (2015) observed soil water depletion of 0.67 to 5.3 cm from the 0 to 90 cm soil profile under three winter cover crop mixes compared to a fallow system during two winter seasons (January to March). In contrast, Alcántara et al. (2011) reported no significant reductions in soil water due to growing and late mowing (24 April) of cruciferous cover crops when compared with a bare soil control in a field experiment in southern Spain. Therefore, the distribution of precipitation in the spring and the termination date of cover crops play an important role in soil water storage.

EFFECT OF WINTER WHEAT COVER CROP ON SEED COTTON YIELD

The simulated seed cotton yield and growing season precipitation from 2001 to 2015 for the CwoC-I, CwC-I, CwoC-D,

Table 5. Comparison of observed (Obs.) and simulated onset dates of cotton phenological stages during CSM-CROPGRO-Cotton module calibration and evaluation.[a]

	Obs.[b]	CwoC-I	CwC-I	CwoC-D	CwC-D
Calibration					
Emergence	4-9	6	6	6	6
Anthesis	60-70	63	63	63	63
Physiological maturity	130-160	136	137	132	134
Evaluation					
Emergence	4-9	6	6	6	6
Anthesis	60-70	61-65	61-65	61-66	61-66
Physiological maturity	130-160	138-140	132-138	129-139	130-139

[a] CwoC-I = irrigated cotton without cover crop, CwC-I = irrigated cotton with cover crop, CwoC-D = dryland cotton without cover crop, and CwC-D = dryland cotton with cover crop.

[b] Robertson et al. (2007).

Table 6. Comparison of typical observed and simulated onset dates of winter wheat phenological stages during CSM-CERES-Wheat module calibration and evaluation.[a]

	Observed[b]	CwC-I	CwC-D
Calibration			
Emergence	2-10	2-18	2-18
Anthesis	145-165	153-162	153-158
Physiological maturity	170-200	NA	NA
Evaluation			
Emergence	2-10	2-7	2-7
Anthesis	145-165	160-165	160-165
Physiological maturity	170-200	NA	NA

[a] CwC-I = irrigated cotton with cover crop, and CwC-D = dryland cotton with cover crop. NA = not applicable; winter wheat was terminated prior to maturity.

[b] From cover crop experiments at Chillicothe, Texas.

and CwC-D treatments are presented in figure 8. When compared to the CwoC treatment, the simulated seed cotton yield for the CwC treatment changed within a range of -10.9% and 0% (average of -4.5%) under irrigated conditions and within a range of -20.2% and 10.1% (average of -6.3%) under rainfed conditions. Under irrigated conditions, for accurate comparison of the effects of cover crops, the amount of irrigation water applied was kept the same for the CwoC-I and CwC-I treatments in this study. In an alternate scenario, when auto-irrigation was used for the CwC-I treatment, about 5% (average over 2001-2015) more irrigation water was applied to the cotton crop, and the average simulated seed cotton yield was reduced by only 2% (range of -6.4% to 4.3%) under the CwC-I treatment when compared to the CwoC-I treatment (results not shown). The simulated seed cotton yield was found to be sensitive to the winter wheat termination date. In general, producers vary the cover crop termination date depending on weather conditions and soil water status. However, in these long-term simulations, the cover crop termination date was set as 20 April for all years, which resulted in higher interannual differences in seed cotton yield between the CwC and CwoC treatments, especially under dryland conditions (fig. 8). Overall, the results from this study indicate that the effect of a winter wheat cover crop on seed cotton yield was not substantial under the simulated conditions at Chillicothe.

Long-term (17 years) winter cover crop studies conducted in cotton production systems at the University of Arkansas Delta Branch Station showed both positive and negative results on cotton yield in individual years (Keisling et al., 1994). The researchers reported that cotton yields in cover crop treatments were lower in years with a dry spring

Table 7. Model performance statistics obtained during the calibration and evaluation of the CROPGRO-Cotton module.[a]

			Seed Cotton Yield (kg ha^{-1})			Statistics for Entire Calibration or Evaluation Period			
	Year	Treatment[b]	Measured[c]	Simulated	PE	PE	%RMSE	d	r^2
Calibration (n = 4)	2013	CwC-I	2752 ±276	2421	-12.0	-10.1	11.9	0.99	0.99
	2013	CwoC-I	2862 ±85	2551	-10.9				
	2013	CwC-D	1334 ±60	1239	-7.1				
	2013	CwoC-D	1123 ±99	1005	-10.5				
Evaluation (n = 8)	2014	CwC-I	3500 ±236	2217	-36.7	-1.0	27.6	0.95	0.47
	2014	CwoC-I	3148 ±389	2406	-23.6				
	2014	CwC-D	1413 ±202	1366	-3.3				
	2014	CwoC-D	1648 ±322	1698	3.0				
	2015	CwC-I	2889 ±123	2936	1.6				
	2015	CwoC-I	2178 ±99	3026	38.9				
	2015	CwC-D	1422 ±28	1404	-1.3				
	2015	CwoC-D	1389 ±94	1571	13.1				

[a] PE = percent error, %RMSE = percent root mean square error, d = index of agreement, and r^2 = coefficient of determination.

[b] CwoC-I = irrigated cotton without cover crop, CwC-I = irrigated cotton with cover crop, CwoC-D = dryland cotton without cover crop, and CwC-D = dryland cotton with cover crop.

[c] Measured seed cotton yield shown as average yield of four replications ± standard deviation.

Table 8. Model performance statistics obtained during the calibration and evaluation of the CERES-Wheat module.[a]

			Aboveground Biomass (kg ha^{-1})			Statistics for Entire Calibration or Evaluation Period			
	Year/Season	Treatment[b]	Measured[c]	Simulated	PE	PE	%RMSE	d	r^2
Calibration (n = 3)	2012-2013	CwC-I	1995 ±174	2123	6.4	8.9	9.1	1.0	0.99
	2011-2012	CwC-D	2540 ±355	2779	9.4				
	2012-2013	CwC-D	1352 ±186	1501	11.0				
Evaluation (n = 4)	2013-2014	CwC-I	1231 ±146	1605	30.4	-0.9	21.8	0.98	0.72
	2014-2015	CwC-I	2614 ±532	2611	-0.1				
	2013-2014	CwC-D	893 ±93	877	-1.8				
	2014-2015	CwC-D	1947 ±353	1323	-32.0				

[a] PE is percent error, %RMSE is percent root mean square error, d is index of agreement, and r^2 is coefficient of determination.

[b] CwC-I = irrigated cotton with cover crop, and CwC-D = dryland cotton with cover crop.

[c] Measured aboveground wheat biomass yield shown as average yield of four replications ± standard deviation.

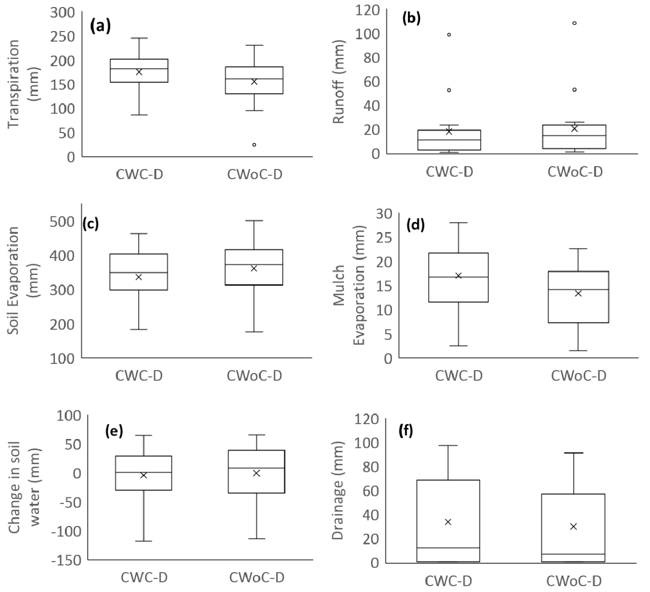

Figure 6. Simulated annual water balance components (2001-2015) including (a) transpiration, (b) runoff, (c) soil evaporation, (d) mulch evaporation, (e) change in soil water, and (d) drainage under dryland cotton production systems with cover crops (CwC-D) and without cover crops (CwoC-D). The × symbol and horizontal line in each box indicate the mean and 50th percentile, respectively. Small circles outside the boxes represent outliers or values greater than 1.5 interquartile ranges away from the 25th or 75th percentiles.

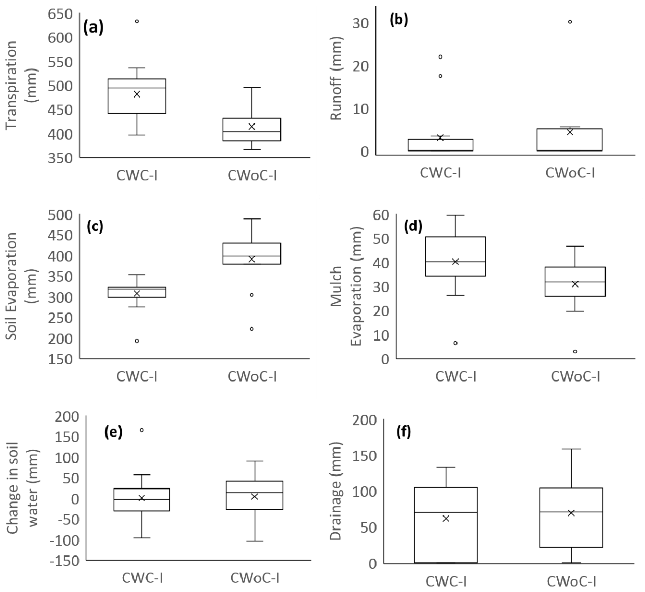

Figure 7. Simulated annual water balance components (2001-2015) including (a) transpiration, (b) runoff, (c) soil evaporation, (d) mulch evaporation, (e) change in soil water, and (d) drainage under irrigated cotton production systems with cover crops (CwC-I) and without cover crops (CwoC-I). The × symbol and horizontal line in each box indicate the mean and 50th percentile, respectively. Small circles outside boxes represent outliers or values greater than 1.5 interquartile ranges away from the 25th or 75th percentiles.

and early summer and higher in years with a normal spring and good rainfall in July and August. Similarly, field studies conducted in the TRP region have also reported no effect of winter cover crop on cotton yield (Baughman et al., 2007; DeLaune et al., 2012). In another field experiment in the Coastal Plain region of North Carolina, cover crops reduced corn yields due to the depletion of soil water during the early-spring conditions (Ewing et al., 1991). Although cover crop practices, in general, improve soil physical properties through faster infiltration and transmission of water, less crusting, and improved soil tilth, there was no guarantee of yield increase for the succeeding cash crops based on the results reported in the literature. Currently, the DSSAT CSM can simulate crop rotations very well, as demonstrated in this study, especially

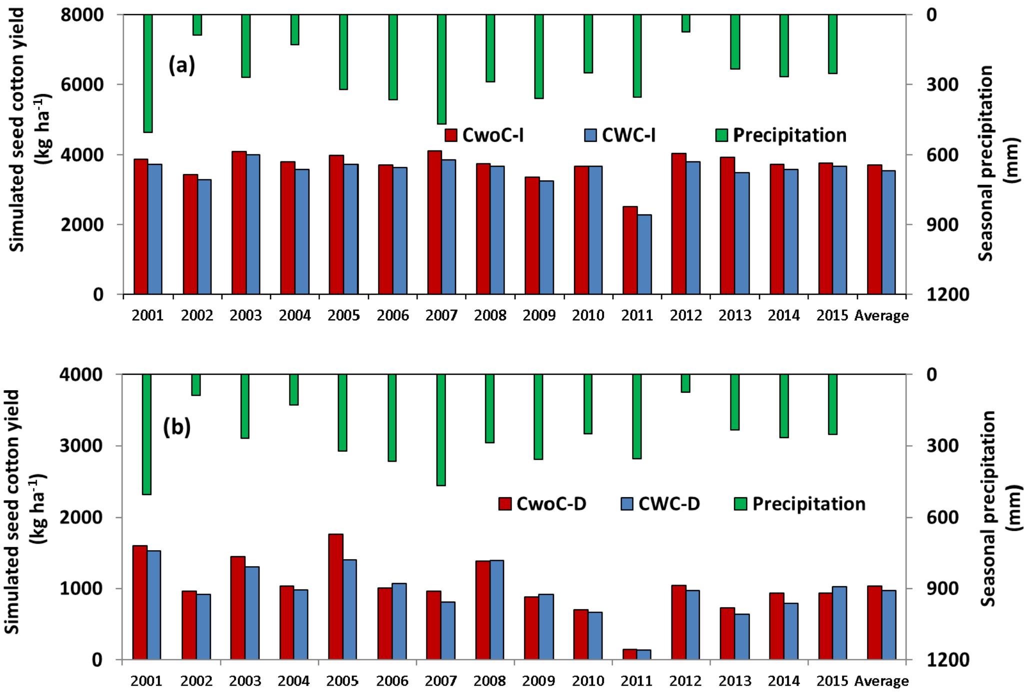

Figure 8. Simulated long-term (2001-2015) seed cotton yields for (a) irrigated cotton without cover crop (CwoC-I) and with cover crop (CwC-I) and (b) dryland cotton without cover crop (CwoC-D) and with cover crop (CwC-D).

the dynamic soil water, nitrogen, and carbon simulations, as well as the simulation of a mulch layer on the surface. However, the current version of DSSAT cannot simulate dynamic changes in soil tilth that could occur during long-term crop rotations.

CONCLUSIONS

The CSM-CROPGRO-Cotton and CSM-CERES-Wheat models were successfully calibrated and evaluated for the TRP region using observed soil water and crop yield data from cover crop experiments (winter wheat as a cover crop followed by cotton) at the Texas A&M AgriLife Research Station at Chillicothe. The models demonstrated the potential to reasonably simulate soil water, seed cotton yield, and aboveground biomass of wheat under both irrigated and dryland conditions. The evaluated wheat and cotton modules were used to simulate the long-term (2001-2015) effects of growing winter wheat as a cover crop on soil water and seed cotton yield. Detailed water balance analysis showed no substantial differences in the average change in soil water between the CwC and CwoC treatments in both dryland and irrigated systems. Similarly, there was no substantial effect of cover crops on average seed cotton yield under both irrigated and dryland conditions. These results imply that winter wheat is a feasible cover crop for TRP cotton production, as it did not affect the soil water availability nor the yield for the succeeding cotton crop under the simulated conditions. Future efforts will focus on better quantifying the soil and water conservation effects of cover crops for the TRP region by identifying ideal cover crop termination dates and assessing the effects of cover crops on carbon and nitrogen balances in cotton production systems.

ACKNOWLEDGEMENTS

We gratefully acknowledge the funding support provided by Cotton Incorporated for this research study.

REFERENCES

Adhikari, P., Ale, S., Bordovsky, J. P., Thorp, K. R., Modala, N. R., Rajan, N., & Barnes, E. M. (2016). Simulating future climate change impacts on seed cotton yield in the Texas High Plains using the CSM-CROPGRO-Cotton model. *Agric. Water Mgmt., 164*(part 2), 317-330. https://doi.org/10.1016/j.agwat.2015.10.011

Alcantara, C., Pujadas, A., & Saavedra, M. (2011). Management of cruciferous cover crops by mowing for soil and water conservation in southern Spain. *Agric. Water Mgmt., 98*(6), 1071-1080. https://doi.org/10.1016/j.agwat.2011.01.016

Attia, A., Rajan, N., Xue, Q., Nair, S., Ibrahim, A., & Hays, D. (2016). Application of DSSAT-CERES-Wheat model to simulate winter wheat response to irrigation management in the Texas High Plains. *Agric. Water Mgmt., 165*, 50-60. https://doi.org/10.1016/j.agwat.2015.11.002

Balkcom, K., Schomberg, H., Reeves, W., Clark, A., Baumhardt, L., Collins, H., ... Mitchell, J. (2007). Managing cover crops in conservation tillage systems. In A. Clark (Ed.), *Managing cover crops profitably* (3rd ed., pp. 44-61). Beltsville, MD: United Book Press.

Baughman, T., Keeling, W., & Boman, R. (2007). On-farm conservation tillage programs to increase dryland cotton profitability. Final report to Cotton Incorporated. Project No. 05-643TX. Cary, NC: Cotton Incorporated.

Baumhardt, R. L., & Lascano, R. J. (1999). Water budget and yield of dryland cotton intercropped with terminated winter wheat. *Agron. J., 91*(6), 922-927. https://doi.org/10.2134/agronj1999.916922x

Bordovsky, D. G., Choudhary, M., & Gerard, C. J. (1999). Effect of tillage, cropping, and residue management on soil properties in the Texas Rolling Plains. *Soil Sci., 164*(5), 331-340. https://doi.org/10.1097/00010694-199905000-00005

Clark, A. (2007). *Managing cover crops profitably* (3rd ed.). College Park, MD: Sustainable Agriculture Research and Education (SARE).

Dabney, S. M., Delgado, J. A., & Reeves, D. W. (2001). Using winter cover crops to improve soil and water quality. *Comm. Soil Sci. Plant Anal., 32*(7-8), 1221-1250. https://doi.org/10.1081/CSS-100104110

Daggupati, P., Pai, N., Ale, S., Douglas-Mankin, K. R., Zeckoski, R., Jeong, J., ... Youssef, M. A. (2015). A recommended calibration and validation strategy for hydrologic and water quality models. *Trans. ASABE, 58*(6), 1705-1719. https://doi.org/10.13031/trans.58.10712

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

DeLaune, P., & Trostle, C. (2012). Nitrates in irrigation water: An asset for crop production. Extension Publication E-619. Lubbock, TX: Texas A&M AgriLife Extension Service.

Dozier, M., Morgan, G., & Sij, J. (2008). Best management practices to reduce nitrate impacts in ground water and to assess atrazine and arsenic concentrations in private water wells. Final report. Temple, TX: Texas State Soil and Water Conservation Board.

Ewing, R. P., Wagger, M. G., & Denton, H. P. (1991). Tillage and cover crop management effects on soil water and corn yield. *SSSA J., 55*(4), 1081-1085. https://doi.org/10.2136/sssaj1991.03615995005500040031x

He, J., Cai, H., & Bai, J. (2013). Irrigation scheduling based on CERES-Wheat model for spring wheat production in the Minqin oasis in northwest China. *Agric. Water Mgmt., 128*, 19-31. https://doi.org/10.1016/j.agwat.2013.06.010

Hoogenboom, G., Jones, J. W., Wilkens, P. W., Porter, C. H., Boote, K. J., Hunt, L. A., ... Tsuji, G. Y. (2010). Decision Support System for Agrotechnology Transfer (DSSAT) version 4.5. Honolulu, HI: University of Hawaii.

Hoogenboom, G., Jones, J. W., Wilkens, P. W., Porter, C. H., Boote, K. J., Hunt, L. A., ... Tsuji, G. Y. (2015). Decision Support System for Agrotechnology Transfer (DSSAT) version 4.6. Prosser, WA: DSSAT Foundation. Retrieved from www.DSSAT.net

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

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

Keeling, J. W., Matches, A. G., Brown, C. P., & Karnezos, T. P. (1996). Comparison of interseeded legumes and small grains for cover crop establishment in cotton. *Agron. J., 88*(2), 219-222. https://doi.org/10.2134/agronj1996.00021962008800020017x

Keisling, T. C., Scott, H. D., Waddle, B. A., Williams, W., & Frans, R. E. (1994). Winter cover crops influence on cotton yield and selected soil properties. *Comm. Soil Sci. Plant Anal., 25*(19-20), 3087-3100. https://doi.org/10.1080/00103629409369250

Lascano, R. J., Krieg, D. R., Baker, J. T., Goebel, T. S., & Gitz, D. C. (2015). Planting cotton in a crop residue in a semiarid climate: Water balance and lint yield. *Open J. Soil Sci., 5*(10), 236-249. https://doi.org/10.4236/ojss.2015.510023

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

Li, L., Malone, R. W., Ma, L., Kaspar, T. C., Jaynes, D. B., Saseendran, S. A., ... Ahuja, L. R. (2008). Winter cover crop effects on nitrate leaching in subsurface drainage as simulated by RZWQM-DSSAT. *Trans. ASABE, 51*(5), 1575-1583. https://doi.org/10.13031/2013.25314

Lobell, D. B., & Ortiz-Monasterio, J. I. (2006). Evaluating strategies for improved water use in spring wheat with CERES. *Agric. Water Mgmt., 84*(3), 249-258. https://doi.org/10.1016/j.agwat.2006.02.007

Mitchell, J. P., Shrestha, A., & Irmak, S. (2015). Trade-offs between winter cover crop production and soil water depletion in the San Joaquin Valley, California. *J. Soil Water Cons., 70*(6), 430-440. https://doi.org/10.2489/jswc.70.6.430

Modala, N. R., Ale, S., Rajan, N., Munster, C., DeLaune, P. B., Thorp, K. R., ... Barnes, E. M. (2015). Evaluation of the CSM-CROPGRO-cotton model for the Texas Rolling Plains region and simulation of deficit irrigation strategies for increasing water use efficiency. *Trans. ASABE, 58*(3), 685-696. https://doi.org/10.13031/trans.58.10833

NRCS. (2017). Soil health. Washington, DC: USDA Natural Resources Conservation Service. Retrieved from https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/

Panda, R. K., Behera, S. K., & Kashyap, P. S. (2003). Effective management of irrigation water for wheat crop under stressed conditions using simulation modeling. *Proc. 7th Intl. Water Tech. Conf.* (pp. 35-57). Retrieved from http://www.iwtc.info/2003_pdf/01-3.pdf

Porter, D., Marek, T., Howell, T., & New, L. (2005). *Texas High Plains Evapotranspiration Network (TXHPET) user manual*. Publication AREC 05-37. Amarillo, TX: Texas AgriLife Research and Extension Center.

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

Robertson, B., Bednarz, C., & Burmester, C. (2007). Growth and development: First 60 days. *Cotton Physiology Today*, *13*(2). Memphis, TN: National Cotton Council.

Salmeron, M., Cavero, J., Isla, R., Porter, C. H., Jones, J. W., & Boote, K. J. (2014). DSSAT nitrogen cycle simulation of cover crop: Maize rotations under irrigated Mediterranean conditions. *Agron. J., 106*(4), 1283-1296. https://doi.org/10.2134/agronj13.0560

Sij, J. W., Ott, J. P., Olson, B. L., Baughman, T. A., & Bordovsky, D. G. (2004). Dryland cropping systems to enhance soil moisture capture and water use efficiency in cotton. *Proc. Beltwide Cotton Conf.* Memphis, TN: National Cotton Council.

Thorp, K. J., Hunsaker, D. J., French, A. N., White, J. W., Clarke, T. R., & Pinter Jr, P. J. (2010). Evaluation of the CSM-CROPSIM-CERES-Wheat model as a tool for crop water management. *Trans. ASABE, 53*(1), 87-102. https://doi.org/10.13031/2013.29505

Timsina, J., Godwin, D., Humphreys, E., Yadvinder, S., Bijay, S., Kukal, S. S., & Smith, D. (2008). Evaluation of options for increasing yield and water productivity of wheat in Punjab, India, using the DSSAT-CSM-CERES-Wheat model. *Agric. Water Mgmt., 95*(9), 1099-1110. https://doi.org/10.1016/j.agwat.2008.04.009

Uryasev, O., Gijsman, A. J., Jones, J. W., & Hoogenboom, G. (2004). DSSAT v4 Soil data editing program [Sbuild]. In P. W. Wilkens, G. Hoogenboom, C. H. Porter, J. W. Jones, & O. Uryasev (Eds.), *Decision support system for agrotechnology transfer, Ver. 4.0: Data management and analysis tools* (vol. 2). Honolulu, HI: University of Hawaii.

USDA. (2008). General soil map of Texas. Temple, TX: USDA Natural Resources Conservation Service. Retrieved from http://www.lib.utexas.edu/maps/texas/texas-general_soil_map-2008.pdf

USDA. (2012). Texas agricultural statistics. Bulletin 268. Washington, DC: USDA National Agricultural Statistics Service.

Veenstra, J. J., Horwath, W. R., & Mitchell, J. P. (2007). Tillage and cover cropping effects on aggregate-protected carbon in cotton and tomato. *SSSA J., 71*(2), 362-371. https://doi.org/10.2136/sssaj2006.0229

Willmott, C. J., Ackleson, S. G., Davis, R. E., Feddema, J. J., Klink, K. M., Legates, D. R., ... Rowe, C. M. (1985). Statistics for the evaluation and comparison of models. *J. Geophys. Res. Oceans, 90*(C5), 8995-9005. https://doi.org/10.1029/JC090iC05p08995

Yang, J. M., Yang, J. Y., Liu, S., & Hoogenboom, G. (2014). An evaluation of the statistical methods for testing the performance of crop models with observed data. *Agric. Syst., 127*, 81-89. https://doi.org/10.1016/j.agsy.2014.01.008