EVALUATION OF CSM-CROPGRO-COTTON FOR SIMULATING EFFECTS OF MANAGEMENT AND CLIMATE CHANGE ON COTTON GROWTH AND EVAPOTRANSPIRATION IN AN ARID ENVIRONMENT

K. R. Thorp, E. M. Barnes, D. J. Hunsaker, B. A. Kimball,
J. W. White, V. J. Nazareth, G. Hoogenboom

ABSTRACT. *Originally developed for simulating soybean growth and development, the CROPGRO model was recently re-parameterized for cotton. However, further efforts are necessary to evaluate the model's performance against field measurements for new environments and management options. The objective of this study was to evaluate CSM-CROPGRO-Cotton using data from five cotton experiments conducted at the Maricopa Agricultural Center in Maricopa, Arizona. The field experiments tested ambient atmospheric carbon dioxide (CO_2) versus free-air CO_2 enrichment (FACE) over two growing seasons (1990 and 1991), two irrigation levels and two nitrogen fertilization levels for one growing season (1999), and three planting densities and two nitrogen fertilization levels with optimum irrigation for two growing seasons (2002 and 2003). The model was calibrated by adjusting cultivar and soil parameters for the most optimal or standard treatment of each field trial, and the model's responses to suboptimal irrigation, suboptimal nitrogen fertilization, non-standard planting density, and CO_2 enrichment were evaluated. Modifications to the model's evapotranspiration (ET) routines were required for more realistic ET simulations in the arid conditions of central Arizona because default approaches underestimated seasonal ET up to 157 mm (15% of mean values). Data quality and availability among the field trials were highly variable, but the combination of data sets from multiple field investigations permitted a more thorough model evaluation. Simulations of leaf area index, canopy weight, canopy height, and canopy width responded appropriately compared to measurements from experimental treatments, although some experiments did not impose enough treatment variability to elicit substantial model responses. Simulation results for densely planted cotton were particularly deficient as compared to other experimental treatments. The model simulated seed cotton yield with root mean squared errors ranging from 105 to 1107 kg ha^{-1} (3% to 28% of mean values), and total seasonal ET was simulated with root mean squared errors ranging from 12 to 42 mm (1% to 5% of mean values). Seed cotton yield and ET variability due to the imposed experimental treatments were simulated appropriately ($p < 0.05$), independent of the year-to-year variability due to seasonal factors. Modification of the ET routines permitted maximum simulated crop coefficients ranging from 1.31 to 1.35, which were more realistic than that required for default ET methods in the model. Overall, the evaluation demonstrated appropriate model responses to water deficit, nitrogen deficit, planting density, and CO_2 enrichment. Potential opportunities for further model improvement include the estimation of crop responses to high planting densities, the simulation of cotton maturity and defoliation events, and the calculation of canopy temperature as part of a complete energy balance algorithm.*

Keywords. *Biomass, Canopy height, Cotton, Crop, Density, Evapotranspiration, FACE, Fertilizer, Free-air carbon dioxide enrichment, Irrigation, Leaf area index, Model, Nitrogen, Population, Simulation, Water, Yield.*

The application of cropping system simulation models in a variety of cotton (*Gossypium hirsutum* and *Gossypium barbadense*) research areas has increased during the last decade and continues to grow (Thorp et al., 2014). The models have found applicability for studying cotton water use and irrigation water management, nitrogen (N) dynamics and fertilizer management, genetics and crop improvement, impacts of climatology and global climate change on cotton production, precision agriculture approaches for cotton crop management, and the economics of cotton production. In the fu-

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The authors are **Kelly R. Thorp, ASABE Member,** Research Agricultural Engineer, USDA-ARS Arid Land Agricultural Research Center, Maricopa, Arizona; **Edward M. Barnes, ASABE Member,** Senior Director of Agricultural and Environmental Research, Cotton Incorporated, Cary, North Carolina; **Douglas. J. Hunsaker, ASABE Member**, Research Agricultural Engineer, **Bruce A. Kimball,** Retired Collaborator, and **Jeffrey W. White,** Research Plant Physiologist, USDA-ARS Arid Land Agricultural Research Center, Maricopa, Arizona; **Vijay J. Nazareth,** Research Assistant, International Food Policy Research Institute, Washington, D.C.; **Gerrit Hoogenboom, ASABE Member,** Director, AgWeatherNet, Washington State University, Prosser, Washington. **Corresponding author:** Kelly R. Thorp, USDA-ARS ALARC, 21881 N. Cardon Lane, Maricopa, AZ 85138; phone: 520-316-6375; e-mail: kelly.thorp@ars.usda.gov.

ture, cotton simulation models are expected to find additional applicability for life-cycle assessments and as components of broader software and hardware systems that optimize cotton management while considering potential environmental impacts, resource constraints, and climate predictions. While the upward trend for cotton model applications is positive, attention should not be diverted from efforts to evaluate and improve the models. When such efforts lead to modifications and improvements in the computer code, the models become more reliable, better structured, more flexible, and more easily used by people with diverse backgrounds and levels of modeling experience.

The CROPGRO-Cotton model is a crop growth simulation algorithm within the Cropping System Model (CSM; Jones et al., 2003), as distributed with the Decision Support System for Agrotechnology Transfer (DSSAT; Hoogenboom et al., 2012). Originally, CROPGRO was developed for grain legumes (Hoogenboom et al., 1992), including soybean (*Glycine max*) and peanut (*Arachis hypogaea*), and DSSAT lacked a module for fiber crops. Because of the importance of cotton in the southeastern U.S., especially in rotation with peanut, a comprehensive model for cotton was needed. Rather than developing a new model, CROPGRO was used as a template. The CROPGRO-Cotton module could then be added to the CSM without creating new utilities for data input/output and new algorithms for soil water and nutrient balance simulations. Another advantage was the CSM's existing functionality for continuous simulation of crop rotations. Because the CSM handles differences in crop species through external genotype files, emphasis was placed on obtaining detailed physiological information to define genotype parameters for cotton and experimental data for initial model calibration and evaluation. The CSM-CROPGRO-Cotton model was developed through a collaborative effort among scientists at the University of Florida and the University of Georgia (Messina et al., 2004; Pathak et al., 2007; Soler and Hoogenboom, 2005, 2006).

Applications of CSM-CROPGRO-Cotton have focused mainly in the humid southeastern U.S., where simulation studies were used to determine irrigation water use for Georgia (Guerra et al., 2007), to assess the impact of climate variability and the El Niño/La Niña Southern Oscillation (ENSO) on yield under different management options (Garcia y Garcia et al., 2010; Paz et al., 2012), to test model sensitivity to solar radiation (Garcia y Garcia et al., 2008) and other inputs (Pathak et al., 2007), to analyze crop insurance options and reduce farm risk given ENSO climate variability (Cabrera et al., 2006), and to study the impact of southern root-knot nematodes on cotton growth and yield (Ortiz et al., 2009). Other applications include a climate change study in Cameroon (Gérardeaux et al., 2013) and an agronomic and economic evaluation of cotton irrigation strategies in Australia (Cammarano et al., 2012). While many of these studies included basic efforts to evaluate the model using field experimental data, their main focus was to address a specific application of the model. Likely, data availability impacted model evaluation efforts for these studies. Finally, no studies report evaluations or applications of CSM-CROPGRO-Cotton for arid and semi-arid cotton production regions in the western U.S., such as the west Texas High Plains, the central Arizona valley, or the San Joaquin Valley in California.

Agronomic field experiments for cotton have been routinely conducted over the past three decades at the Maricopa Agricultural Center in Maricopa, Arizona. In 1990 and 1991, field experiments compared cotton growth, yield, and water use for ambient atmospheric carbon dioxide (CO_2) concentration ([CO_2]) and free-air CO_2 enrichment with two irrigation levels (Hunsaker et al., 1994; Mauney et al., 1994). In 1999, cotton was managed using two irrigation levels and two N fertilization levels to test the ability of a ground-based remote sensing system to detect water and N stress (El-Shikha et al., 2008; Haberland et al., 2010; Kostrzewski et al., 2002). In 2002 and 2003, field experiments tested irrigation scheduling strategies using basal crop coefficients based on remote sensing and FAO-56 (Allen et al., 1998) for three levels of plant density and two levels of N fertilization (Hunsaker et al., 2005). Data availability and quality varied among these field trials, but information on cotton development, leaf area index (LAI), aboveground biomass weight, canopy height and width, seed and fiber yield, and evapotranspiration (ET) was generally collected for all studies. Since these studies provided ample data for understanding cotton growth, yield, and water use responses to a variety of management practices and local environmental conditions, the objective of this study was to perform a comprehensive evaluation of the CSM-CROPGRO-Cotton model for irrigated cotton in the arid conditions of central Arizona.

Materials and Methods

CSM-CROPGRO-Cotton

The DSSAT CSM (ver. 4.5.1.005) is an ecophysiological model that programmatically synthesizes current knowledge of cropping system processes (Jones et al., 2003). The model utilizes mass balance principles to simulate the carbon (C), N, and hydrologic processes and transformations that occur within a cropping system. Simulations of crop development and growth for over 28 crop species are possible, but this study used only CSM-CROPGRO-Cotton. The CSM calculates cropping system processes within a homogeneous area on a daily time step, and certain subprocesses are computed hourly. Crop development proceeds through a series of growth stages based on photothermal unit accumulation from planting to harvest, including emergence, first leaf, first flower, first seed, first cracked boll (physiological maturity), and 90% open boll. The model also calculates flower and boll number and fruit abortion. Light interception is simulated based on a hedgerow canopy, where the plant canopy envelope is elliptical and defined by simulated canopy height and width (Boote and Pickering, 1994). Potential C assimilation is computed from leaf-level biochemistry based on the model of Farquar et al. (1980), and deductions for growth and maintenance respiration are calculated explicitly. The model calculates stress effects from deficit soil water and soil N conditions, which further reduce the carbohydrate available for plant growth. Assimilated C is partitioned to various plant parts, including leaves, stems, roots, bolls, and seed cotton (seed + fiber). Leaf senescence is simulated in response to natural aging, N remobilization, water deficits, light stress, and physiological maturity. Both deficit and excess soil water conditions lead to root senescence.

Simulated plant growth responds to management practices, cultivar selection, soil properties, and meteorological conditions. Management inputs required for model simulations include plant population; row spacing; seed depth; planting dates; dates and amounts of irrigation; dates, amounts, and type of fertilizer application; and dates, depths, and type of tillage. Cultivar parameters define day length sensitivity, heat units needed to progress through growth stages, maximum single leaf photosynthetic rate, single leaf size, specific leaf area, maximum partitioning to bolls, individual seed size, threshing percentage, and oil and protein composition of seeds. Soil profiles are defined by soil water limits (lower limit of plant extractable water, drained upper limit, and saturated soil water content), root growth factors, saturated hydraulic conductivity, bulk density, pH, and initial conditions for water, inorganic N, and organic C. Surface soil parameters include albedo, drainage rate, and runoff curve number. Minimum data requirements for meteorological observations include minimum and maximum temperature, solar irradiance, and precipitation on a daily basis. Inclusion of wind speed and dew point temperature data permit additional ET calculation options. A single value for [CO_2] can be specified in the weather file. Alternatively, the model can obtain [CO_2] from an external file that provides measurements from the long-term atmospheric [CO_2] monitoring site on Mauna Loa in Hawaii (www.esrl.noaa.gov/gmd/ccgg/trends/).

Water deficits in the CSM are represented by two stress factors: one that affects the turgor-based growth processes and another that affects photosynthesis and growth processes. Water deficits are simulated when the potential demand for water lost through transpiration and soil water evaporation is higher than the amount of water that can be supplied by the soil through the root system (Anothai et al., 2013). Evaporative demand is calculated using either the Priestley-Taylor equation (Priestley and Taylor, 1972) or a Penman-Monteith approach based on FAO-56, although the current FAO-56 approach deviates somewhat from Allen et al. (1998) in the calculation of reference evapotranspiration (ET_o). In this study, potential ET (PET) was calculated using a new approach that combined the ASCE Standardized Reference Evapotranspiration Equation (Walter et al., 2005) with the approach of DeJonge et al. (2012) for calculation of a crop coefficient (K_c) as a function of LAI. A new subroutine was added to the model to calculate ET_o using the ASCE method, and PET was calculated from ET_o based on K_c:

$$K_c = 0.35 + (\text{EORATIO} - 0.35) \times (1 - \exp(-0.70 \times \text{LAI})) \quad (1)$$

$$\text{PET} = K_c \times \text{ET}_o \quad (2)$$

Equation 1 was adapted from DeJonge et al. (2012) using a minimum cotton crop coefficient of 0.35 (Allen et al., 1998). The EORATIO parameter represents a maximum crop coefficient. The soil water balance in the CSM uses a tipping bucket approach for a one-dimensional soil profile (Ritchie, 1972, 1998; Ritchie et al., 2009). Daily evaporative demand is calculated first, and the potential water supply for root uptake is based on the soil water content, root distribution, and root growth factor in each layer. If the potential supply is greater than the potential demand, the supply is set equal to the demand, and the associated processes are updated. If the demand is greater than the supply, transpiration and soil water evaporation are reduced to the simulated supply, and water deficit stress factors are calculated based on the difference between potential demand and potential supply.

The CSM includes a detailed soil and plant N balance (Godwin and Singh, 1998). Although the original CROPGRO model included N fixation, the modular structure of the CSM (Jones et al., 2003) permitted the fixation module to be switched off for cotton. The soil N simulation includes a variety of processes that are calculated for each soil horizon or computational layer for the transformation of organic N to inorganic N in the form of nitrate and ammonium. Godwin and Singh (1998) also developed an approach for calculation of processes associated with soil organic C and N. Plant N uptake is based on the potential supply from the soil and the plant N demand. Cultivar parameters for critical N content specify the plant tissue N concentrations below which the plant experiences N stress.

FIELD EXPERIMENTS

Data from five field experiments were used to evaluate responses of the CSM-CROPGRO-Cotton model (table 1). All experiments were conducted at the University of Arizona's Maricopa Agricultural Center (MAC) near Maricopa, Arizona (33.068° N, 111.971° W, 360 m above mean sea level). The environment at MAC is arid, and cotton production requires irrigation. From 1987 to 2011, precipitation during the cotton growing season, from 15 April to 15 October, averaged 67 mm and ranged from 21 to 134 mm. Rainfall typically occurred during the late summer monsoon season, beginning in July. Maximum daily air temperatures from 1987 to 2011 regularly exceeded 38°C during July and August (fig. 1).

FACE Experiments

The effect of free-air carbon dioxide enrichment (FACE) on cotton growth, yield, and water use was field-tested in the summers of 1990 and 1991 (Hunsaker et al., 1994; Mauney et al., 1994). Lewin et al. (1994) described the facility used to elevate the [CO_2] within the cotton canopy to 550 μmol mol^{-1} for 14 h d^{-1} during the growing season. Control plots with ambient atmospheric [CO_2] of 370 μmol mol^{-1} (Nagy et al., 1994) were approximately 100 m from the FACE plots to minimize contamination from FACE treatments without sacrificing soil uniformity. Two irrigation levels were also tested using a subsurface drip irrigation system. Seasonal irrigation rates of 1190 and 1060 mm were applied for wet and dry treatments in 1990, and the irrigation rates for 1991 were 1048 and 792 mm for wet and dry treatments, respectively (table 1). Nitrogen fertiliz-

Table 1. General information for the cotton field experiments in central Arizona.[a]

Experiment	FACE	FACE	AgIIS	FISE	FISE
Year	1990	1991	1999	2002	2003
Planting date	23 April (DOY 113)	16 April (DOY 106)	16 April (DOY 106)	15-16 April (DOY 105-106)	7-8 April (DOY 97-98)
Cotton cultivar	Deltapine 77	Deltapine 77	Deltapine 90b	Deltapine 458	Deltapine 458
Irrigation method	Drip	Drip	Sprinkler	Surface	Surface
Total irrigation	Wet: 1190 mm Dry: 1060 mm	Wet: 1048 mm Dry: 792 mm	Wet: 993 mm Dry: 929 mm	1115 mm	1218 mm
Rainfall	134 mm	23 mm	151 mm	53 mm	50 mm
Total nitrogen fertilizer	155 kg N ha^{-1}	135 kg N ha^{-1}	Low: 112 kg N ha^{-1} High: 222 kg N ha^{-1}	Low: 36 kg N ha^{-1} High: 186 kg N ha^{-1}	Low: 0 kg N ha^{-1} High: 122 kg N ha^{-1}
Canopy [CO_2]	Ambient: 370 μmol mol^{-1} FACE: 550 μmol mol^{-1}	Ambient: 370 μmol mol^{-1} FACE: 550 μmol mol^{-1}	368 μmol mol^{-1}	373 μmol mol^{-1}	376 μmol mol^{-1}
Harvest date	18 September (DOY 261)	17 September (DOY 260)	12 November (DOY 316)	9 October (DOY 282)	17 October (DOY 290)

[a] AgIIS = Agricultural Irrigation Imaging System, [CO_2] = CO_2 concentration, DOY = day of year, FACE = free-air carbon dioxide enrichment, and FISE = FAO-56 irrigation scheduling experiment.

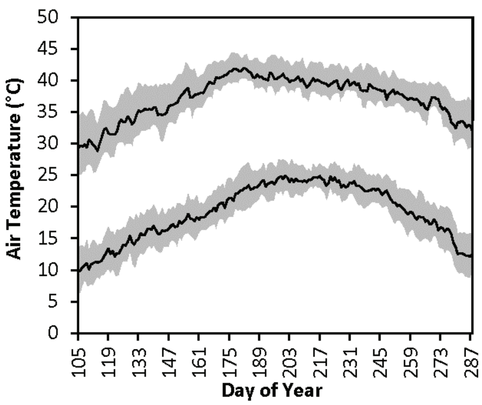

Figure 1. Mean daily maximum and minimum air temperatures from 1987 to 2011 at Maricopa, Arizona. Shaded regions represent one standard deviation from the mean.

er was delivered as split applications through the drip system to ensure non-limiting N conditions. Seasonal rates were 155 and 135 kg ha^{-1} in 1990 and 1991, respectively. Cotton cultivar 'Deltapine 77' was planted in raised beds spaced at 1.02 m on 23 April 1990 and 16 April 1991 and was thinned to 10.0 plant m^{-2} in both growing seasons. The soil was a Trix clay loam (fine-loamy, mixed (calcareous), hyperthermic Typic Torrifluvents) for both FACE experiments.

As described by Mauney et al. (1994), the development of cotton flowers and bolls was monitored daily. Destructive samples of aboveground plant material provided weekly estimates of canopy height, LAI, and canopy weight. To conserve CO_2, final yield was measured on 18 September 1990 and 17 September 1991, approximately one month prior to local production practice. Cotton ET was estimated from neutron probe measurements of soil moisture in 0.2 m increments to a depth of 2.0 m, as described by Hunsaker et al. (1994).

AgIIS Experiment

In the late 1990s, the Agricultural Irrigation Imaging System (AgIIS, pronounced "ag eyes") was developed as a ground-based proximal sensing system for monitoring crop water and N stress at the MAC (Haberland et al., 2010). The vehicle platform for AgIIS was a two-span linear-move irrigation machine, which served the dual role of carrying sensing equipment and applying variable irrigation and N fertigation rates. To test the AgIIS system, a field experiment in the summer of 1999 provided cotton responses to two irrigation levels and two N fertilization levels (El-Shikha et al., 2008; Kostrzewski et al., 2002). Four replications of four treatments, including (1) optimal water and optimal N, (2) optimal water and low N, (3) low water and optimal N, and (4) low water and low N, were tested using a Latin square experimental design. Sprinkler irrigation with AgIIS provided seasonal irrigation rates of 993 and 929 mm for the optimum and low irrigation levels, respectively (table 1). Split applications of N fertilizer using AgIIS provided 222 and 112 kg N ha^{-1} for the optimum and low N levels, respectively. Cotton cultivar 'Deltapine 90b' was planted on 16 April 1999 with a density of 9.4 plant m^{-2} and row spacing of 1.02 m. The soil was a Casa Grande sandy loam (fine-loamy, mixed, hyperthermic, Typic Natrargids).

In addition to the AgIIS canopy reflectance measurements described by Kostrzewski et al. (2002), cotton growth and development were regularly measured over the growing season. Destructive samples of aboveground plant material provided weekly estimates of canopy weight and LAI. Canopy height and width were also measured weekly. Yield measurements were collected on 12 November 1999 but were considered unrepresentative of the imposed treatments due to late-season Lygus (*Lygus hesperus*) infestation. Cotton ET was estimated from neutron probe measurements of soil moisture in 0.2 m increments to a depth of 2.0 m.

FISE Experiments

In 2002 and 2003, the FAO-56 Irrigation Scheduling Experiments (FISE) were conducted to test irrigation scheduling strategies for cotton using basal crop coefficients estimated in two ways: from FAO-56 standard procedures (Allen et al., 1998) and from in-season normalized difference vegetation index (NDVI) measurements of the canopy (Hunsaker et al., 2005). A gated pipe irrigation system delivered water to diked treatment plots using irrigation schedules based on ET_o and basal crop coefficient estimates combined with a soil water balance model. Because the irrigation management of the NDVI-based treatments could vary on a plot-by-plot basis, the present study used data from the standard FAO-56 irrigation scheduling treatments only. To impose variability in crop growth and water use for testing remote sensing methods, experimental subtreatments included three levels of planting density and two levels of N fertilization (table 1). Planting density treatments were sparse (~5.2 plants m^{-2}), typical (~11.5 plants m^{-2}), and dense (~22.1 plants m^{-2}). The blanket pre-plant application of N fertilizer was 36 kg N ha^{-1} in 2002, and no pre-plant N was applied in 2003. Split applications of N fertilizer during the growing season provided 150 and 122 kg N ha^{-1} for the high N treatment in 2002 and 2003, respectively. With the exception of the pre-plant N application in 2002, the low N treatment received no supplemental N fertilizer. Cotton cultivar 'Deltapine 458/RR, Bollgard/Roundup Ready' was planted on 15-16 April 2002 and 7-8 April 2003 with a row spacing of 1.02 m. To achieve the dense planting, cotton was double planted in rows offset by 0.2 m. Post-emergence hand thinning was performed to achieve the sparse plant density. The experimental field and soil type was the same as for the AgIIS experiment described above.

Measurements of cotton growth were less thorough for the FISE experiments as compared to FACE and AgIIS. Observations of canopy height and width were available from mid-June through mid-September on a weekly basis in 2002 and on a more infrequent interval in 2003. Destructive samples of aboveground biomass provided weekly estimates of canopy weight in 2003 only. Final yield was measured on 9 October 2002 and 17 October 2003. Cotton ET was estimated from neutron probe measurements of soil moisture in 0.2 m increments to a depth of 2.8 cm (Hunsaker et al., 2005).

Model Parameterization

The CSM-CROPGRO-Cotton model was parameterized to simulate each experimental treatment in each field study. All crop management inputs, including cotton planting details, irrigation schedules, N fertilizer applications, and final harvest dates, were specified as performed during field trials. Pre-season neutron probe data specified the initial soil water content parameters for each growing season. Pre-season soil inorganic N contents were largely unavailable in these studies; thus, initial soil N conditions were specified based on best estimates from limited data. For the Casa Grande sandy loam at the AgIIS and FISE field site, soil water retention and hydraulic parameters were specified based on a textural analysis of soil samples. The Rosetta pedotransfer functions (Schaap et al., 2001) were used to calculate the required soil input parameters from the textural information. These soil parameters were previously tested for CSM-CROPSIM-CERES-Wheat simulations at the same experimental site (Thorp et al., 2010). For the Trix clay loam at the FACE field site, soil parameters were previously specified and available in DSSAT (Kimball et al., 1992), and these soil parameters were used for the FACE simulations with minimal modification. Meteorological data were obtained from an Arizona Meteorological Network (AZMET; http://ag.arizona.edu/azmet/) station approximately 100 m from the AgIIS and FISE field site and 1 km from the FACE field site. Default parameters for the 'Deltapine 77' and 'Deltapine 458' cotton cultivars were provided in DSSAT, but many of the cultivar parameters required further calibration to improve model simulations as compared to experimental measurements for the studies described above.

Model Calibration and Evaluation

Model calibration was conducted by manual adjustment of 15 parameters to improve simulation results as compared to measurements. Parameters that govern the crop development simulation were adjusted first, since water and N stress effects did not have a large effect on the crop development simulation. Five of the adjusted crop development parameters were from the cultivar file (COGRO045.CUL): photothermal time between plant emergence and flower appearance (EM-FL), photothermal time between first flower and first boll (FL-SH), photothermal time between first flower and first seed (FL-SD), photothermal time between first seed and physiological maturity (SD-PM), and photothermal time between first flower and the end of leaf expansion (FL-LF) (table 2). Two adjusted crop development parameters were from the ecotype file (COGRO045.ECO): thermal time between planting and emergence (PL-EM) and photothermal time from first flower to the last leaf on the main stem (FL-VS). Four adjusted parameters that control crop growth were from the cultivar file: maximum leaf photosynthesis rate (LFMAX; mg CO_2 m^{-2} s^{-1}), specific leaf area under standard conditions (SLAVR; cm^2 g^{-1}), maximum fraction of daily growth that is partitioned to bolls (XFRT), and threshing percentage or maximum ratio of seed cotton weight and boll weight (THRSH). Adjusted parameters controlling the crop width and height simulation were RWDTH and RHGHT, respectively, from the ecotype file. The EORATIO parameter in the species file (COGRO045.SPE) was used in the model's calculation of K_c (eq. 1) and represented the maximum crop coefficient under non-stressed conditions. It was adjusted to improve ET simulations. For some of the field studies, soil parameters were also adjusted to improve simulation of soil moisture as compared to neutron probe data, including root growth factors in each soil layer (SRGF), the drained upper limit of each soil layer (SDUL), and the soil drainage rate (SLDR).

A unique aspect of this study was the use of diverse data sets from multiple field experiments to perform a thorough evaluation of the various components of the CSM-CROPGRO-Cotton model. Because of the differences in available data and experimental objectives among the field studies, the general protocol was to calibrate the model to fit the control treatment or most standard treatment of each field study and to evaluate the model by examining its response to other experimental treatments imposed in a given growing season. In addition, cultivar parameters were specified equally for the studies that used identical cultivars (table 1), and soil parameters were specified equally for studies that used the same field. An exception included the XFRT cultivar parameter, which required adjustment in each growing season to simulate yield appropriately. In addition, as compared to the FISE studies, SDUL parame-

Table 2. Model calibration results.[a]

Parameter	Description	FACE 1990	FACE 1991	AgIIS 1999	FISE 2002	FISE 2003
Cultivar parameters						
EM-FL	Photothermal time between plant emergence and flower appearance	47	47	50	50	50
FL-SH	Photothermal time between first flower and first boll	8	8	10	10	10
FL-SD	Photothermal time between first flower and first seed	13	13	15	15	15
SD-PM	Photothermal time between first seed and physiological maturity	43	43	45	45	45
FL-LF	Photothermal time between first flower and the end of leaf expansion	57	57	60	56	56
LFMAX	Maximum leaf photosynthesis rate (mg CO_2 m^{-2} s^{-1})	1.3	1.3	1.3	1.3	1.3
SLAVR	Specific leaf area under standard conditions (cm^2 g^{-1})	165	165	175	160	160
XFRT	Maximum fraction of daily growth that is partitioned to bolls	0.43	0.81	0.56	0.80	0.92
THRSH	Maximum ratio of seed cotton weight and boll weight (threshing percentage)	70	70	60	70	70
Ecotype parameters						
PL-EM	Thermal time between planting and emergence	6	6	9	12	12
FL-VS	Photothermal time from first flower to the last leaf on the main stem	30	30	40	33	33
RWDTH	Relative width of the ecotype	0.9	0.9	0.9	0.9	0.9
RHGHT	Relative height of the ecotype	0.99	0.99	0.90	0.66	0.66
Other parameters						
EORATIO	Maximum crop coefficient under non-stressed conditions (maximum K_c)	1.31	1.31	1.31	1.35	1.35
SLDR	Drainage rate coefficient	0.29	0.29	0.20	0.20	0.20

[a] AgIIS = Agricultural Irrigation Imaging System, FACE = free-air carbon dioxide enrichment, and FISE = FAO-56 irrigation scheduling experiment.

ters in the lower soil layers were specified differently for AgIIS to improve simulations of soil water content.

Model evaluation was conducted by comparing measured and simulated results graphically and by calculating the root mean squared error (RMSE) and absolute errors between measured and simulated seed cotton yield and ET. Additionally, hierarchical linear regression was conducted to evaluate the model's ability to simulate seed cotton yield and ET, while controlling for year-to-year variability due to seasonal factors. This analysis tested the model's overall response to the experimental treatments imposed, independent of variability explained by the individual experiments. First, two linear regression models were fit to the measured and simulated data:

$$\mathbf{M} = \beta_0 + \beta_1 \mathbf{E} + \varepsilon \quad (3)$$

$$\mathbf{M} = \beta_0 + \beta_1 \mathbf{E} + \beta_2 \mathbf{S} + \varepsilon \quad (4)$$

where **M** is the measured data; **E** is a categorical variable with five levels (i.e., one level for each experiment in table 1); **S** is the simulated data; β_0, β_1, and β_2 are the regression coefficients; and ε is the regression model error. The second step was to use an analysis of variance to compare the two regression models above, specifically to test the reduction in the residual sum of squared error between the first and second model. A significant reduction indicated that the second regression model explained variability above and beyond the first regression model and thus that the additional predictor variable (i.e., the simulation results) provided information beyond the first predictor variable (i.e., the experiment or growing season). The interpretation of a significant hierarchical test result was that CSM-CROPGRO-Cotton explained variability in the measurements that was due to the imposed treatments, independent of variability explained by individual experiments and other seasonal factors. More simply, CSM-CROPGRO-Cotton responded appropriately to the experimental treatments imposed. The statistical analysis was conducted using R software (R Project for Statistical Computing; www.r-project.org).

RESULTS AND DISCUSSION

MODEL CALIBRATION

Model calibration efforts provided parameter estimates for the experimental conditions during each of the five growing seasons (table 2), with identical cultivar parameters for experiments that used the same cotton cultivar (table 1). The calibration efforts also highlighted the limitations of the data sets available for model calibration (table 3). The PL-EM parameter was important for accurate simulations of emergence date. Emergence dates were recorded for all experimental trials, although data for explicit calculation of the 50% plant emergence date were more thorough for the AgIIS and FISE experiments (table 3). Calibrated PL-EM parameters ranged from 6 to 12 photothermal days (table 2). The EM-FL parameter was important for accurate simulations of flowering onset date. Flower count data were most descriptive for the FACE experiments and the 2003 FISE experiment (table 3). For the AgIIS and 2002 FISE studies, flowering dates were estimated from sporadic digital images of the canopy. Cali-

Table 3. Availability and quality of field experimental data for model calibration.[a]

Measurement	FACE 1990	FACE 1991	AgIIS 1999	FISE 2002	FISE 2003
Initial soil water content	H	H	H	H	H
Initial soil nitrogen	L	L	-	-	-
Planting date	H	H	H	H	H
Emergence date	L	L	H	H	H
Flower development	H	H	L	L	H
Boll development	L	L	-	-	L
Seed development	-	-	-	-	-
Desiccation date	-	-	L	H	H
Harvest date	H	H	H	H	H
Leaf area index	H	H	H	L	L
Canopy weight	H	H	H	-	H
Canopy height	H	H	H	H	H
Canopy width	-	-	H	H	H
Seed cotton yield	L	L	L	L	L
Neutron probe data	L	L	H	H	H
Evapotranspiration	H	H	H	H	H

[a] AgIIS = Agricultural Irrigation Imaging System, FACE = free-air carbon dioxide enrichment, FISE = FAO-56 irrigation scheduling experiment, H = high-quality data available, L = low-quality data available, and "-" = no data available.

brated EM-FL parameters were 47 photothermal days for FACE and 50 photothermal days for the AgIIS and FISE studies (table 2). Differences in the PL-EM and EM-FL parameters corresponded to the different cotton cultivars used in the experiments (table 1). However, the calibrated values for PL-EM and EM-FL were all higher than values determined previously by others, as presented in the DSSAT cotton cultivar files. For example, the 'Deltapine 77' and 'Deltapine 458' cultivars in the DSSAT system had values of 4 and 4 photothermal days for PM-EM and values of 34 and 39 for EM-FL, respectively (not shown). Currently, an important limitation of the model is that crop development calculations are based on air temperature. However, in arid irrigated environments such as central Arizona, the temperature within a well-water crop canopy is often substantially lower than that of the surrounding air due to evaporative cooling. Use of air temperature instead of canopy temperature likely caused the simulated crop to develop more rapidly than in reality. Thus, to simulate flowering onset date appropriately in Arizona, values for the EM-FL parameter had to be adjusted higher than that previously calibrated by others for identical cultivars in humid environments.

Data required to calibrate the FL-SH and FL-SD parameters were not available for any of these experiments (table 3). Therefore, these parameters were adjusted slightly in relation to overall growing season length (table 2). The SD-PM parameter specified the photothermal days from first seed to physiological maturity, which highlighted a major deficiency in the model as a result of its lineage from CROPGRO-Soybean. Cotton is a perennial plant and therefore does not mature like soybean. Instead, cotton requires defoliation prior to harvest, which can be accomplished using both chemical sprays and, in an arid environment, termination of irrigation. Counts of the nodes above white flower, a common field technique for estimating cotton maturity (Bourland et al., 2001), were not available for any of the experiments. As a result, the SD-PM parameter was adjusted to 43 photothermal days (table 2) for the 1990 and 1991 FACE experiments based on the harvest dates of those experiments (table 1). For the AgIIS study, SD-PM was adjusted to 45 photothermal days based on estimates of leaf senescence from digital images of the canopy (table 2). For the 2002 and 2003 FISE experiments, SD-PM was adjusted to 45 photothermal days, which provided simulations of first cracked boll a few days after the reported defoliation dates. The total duration from flowering to cotton physiological maturity ranged from 56 to 60 photothermal days (table 2; sum of FL-SD and SD-PM). The FL-LF parameter was important for correctly simulating the end of leaf growth. Calibrated parameters for the FL-LF parameter ranged from 56 to 60 photothermal days based on defoliation dates, digital images of canopy senescence, and measurements of LAI.

The LFMAX parameter was very sensitive, as it affects the rate of leaf-level photosynthesis and C assimilation in the plant. Simulations of canopy weight, LAI, and ET were all affected by changes to this parameter, and a value of 1.3 mg CO_2 m^{-2} s^{-1} was found adequate for all experiments (table 2). After calibration of LFMAX, the SLAVR parameter further affected simulations of specific leaf area and LAI. Calibrated SLAVR values ranged from 160 to 175 cm^2 g^{-1} based on improvements to the simulation of LAI. The XFRT and THRSH parameters governed the simulation of seed cotton yield. No data were available to describe the ratio of seed cotton weight to total boll weight, which would have been useful for setting the THRSH parameter. Seed cotton yield data were also questionable for these experiments (table 3). For both FACE experiments, yield samples were collected one month prior to typical harvest dates (table 1). For the AgIIS study, yields were substantially reduced due to Lygus infestations. For the FISE studies, it was unclear if the yield measurements were recorded as dry weights, as output by the model. Calibrating to wet weights may be the cause for the higher XFRT parameter value for the FISE 2003 experiment (table 2). Unlike the other cultivar parameters, the XFRT parameter had to be adjusted uniquely for each experiment to improve simulations of seed cotton yield. Otherwise, large biases between measured and simulated yield data were possible. Model parameterization for yield simulations was likely hampered by lack of representative and properly processed yield measurements, and future field efforts should focus on improving techniques for measuring cotton yield and yield components.

Canopy height and width simulations were affected by three ecotype parameters: FL-VS, RWDTH, and RHGHT. The FL-VS parameter affected the cessation of stem elongation and was therefore important for accurate canopy height simulations. Calibrated FL-VS values ranged from 30 to 40 photothermal days from the onset of flowering to the last leaf on the main stem (table 2). RWDTH and RHGHT adjusted simulations of row width and height, respectively. Calibrated RWDTH values were 0.9 for all experiments, although canopy width data were available only for the AgIIS and FISE studies (table 3). Calibrated values for RHGHT ranged from 0.66 to 0.99 (table 2) depending on the measured canopy height for non-stressed treatments, which was available for all field experiments (table 3).

Adjustment of the EORATIO parameter (maximum K_c; eq. 1) improved ET simulations as compared to ET estimates from neutron probe data. Calibrated EORATIO values were 1.31 for the FACE and AgIIS experiments and 1.35 for the FISE experiments (table 2). Higher EORATIO values for FISE may be the result of the surface irrigation method used in those studies (table 1), due to greater potential for seepage losses and greater difficulty in quantifying applied irrigation depths. If these issues led to higher ET measurements from the neutron probe data than actually occurred, an increased EORATIO parameter would be expected to compensate for the measurement error. Thorp et al. (2010) reported an EORATIO of 1.8 for wheat (*Triticum aestivum*) simulations at the same experimental site, which is very high and unrealistic for maximum K_c. However, the simulations by Thorp et al. (2010) used the original FAO-56 approach in the CSM. In the present study, modification of the model to include the ASCE Standardized Reference Evapotranspiration Equation (Walter et al., 2005) and the approach of DeJonge et al. (2012) for K_c calculations resulted in a more realistic calibration of the EORATIO parameter. Typical maximum K_c for cotton ranges from 1.06 to 1.42 (figs. 20 and 21 in Allen et al., 1998), and no crop has a K_c as high as 1.8. Since higher maximum K_c values are expected in arid and windy environments (Allen et al., 1998), the calibrated EORATIO values of 1.31 and 1.35 are reasonable and justified in the FAO-56 documentation. Modification of the CSM's ET routines resulted in a model parameterization that better agreed with standardized ET estimation approaches.

Improvements in the simulations of soil water and nutrient balances resulted from adjustments to soil profile parameters (not shown). Soil water content simulations were sensitive to the drained upper limit parameters (SDUL), and adjustment of SDUL in some soil layers improved agreement between measured and simulated soil water content. Adjustments of SDUL were performed only for the FISE and AgIIS studies, which had the most reliable neutron probe data (table 3). The drainage rate parameter (SLDR) also affected soil water content and was adjusted to 0.20 for the Casa Grande sandy loam and 0.29 for the Trix clay loam (table 2) to improve agreement between measured and simulated soil water content. Simulations of canopy weight, LAI, and ET were sensitive to the root growth factors (SRGF). For the FISE studies, calibration of these parameters was possible based on estimated root water extraction from neutron probe data. Since surface irrigations during the FISE studies occurred more infrequently, root water extraction patterns were better estimated, so SRGF estimates from FISE were also used for the AgIIS study. Previous SRGF calibrations as provided for the Trix clay loam in DSSAT were used for the FACE studies with minimal modification. Perhaps the greatest data deficiency for the present study was the lack of initial concentrations of N in the soil profile. This was quantified only for the FACE studies (table 3), but data values were questionable and the methods were not well documented. Model simulations of yield were especially sensitive to the N balance calculations, and manual calibration of the initial soil N concentration parameters was the main approach for adjusting this aspect of the model simulation.

Crop Development Responses

With the exception of the FACE experiments, the model did not typically simulate differences in crop development among the experimental treatments for a given growing season (table 4). For FACE, differences occurred between the two irrigation treatments but were no more than 3 days. In most cases, model parameters could be adjusted to simulate crop development events within one day of measurements. It is important to note that some measurements of crop development were of higher quality than others (table 3). For example, measured maturity dates in table 4 were specified as the harvest date for the FACE studies, the estimated date from digital photos for the AgIIS experiment, and the desiccation date for the FISE studies.

The similarity of crop development among the five growing seasons is striking. The dates of crop planting (table 1) and measured crop emergence (table 4) were no greater than 16 and 8 days apart, respectively. Seasonal climate variability in central Arizona is relatively low, which typically results in a stable and predictable growth cycle when cotton is planted in mid-April. Although this may be desirable for lowering cotton production risks, it is not desirable when the goal is to evaluate the response of cotton simulation models. Measured responses of cotton growth to substantial climate variation are needed to further evaluate the model. For example, data from a field trial where cotton planting dates were varied over many weeks would more rigorously test the model's crop development response to climate variability.

Crop Growth Responses to Irrigation

Simulated LAI, canopy weight, and canopy height responded appropriately to wet and dry irrigation treatments with ambient atmospheric [CO_2] for the 1990 and 1991 FACE studies (fig. 2). Simulations of LAI and canopy weight were underestimated by the model during 1990 (figs. 2a and 2b). This result could be related to missing irrigation data from 11 to 70 days after planting (DAP) in 1990, which was estimated based on the reports of Mauney et al. (1994) and Hunsaker et al. (1994). Simulations of LAI were overestimated by the model during 1991 (fig. 2d), but canopy weight was simulated reasonably (fig. 2e). Early season simulations in 1990 were not different because the dry irrigation treatment was not imposed until 71 DAP, whereas the dry irrigation treatment was imposed at 34 DAP in 1991. The imposed irrigation deficit was also greater in 1991, which was apparent in the simulations. Model simulations of canopy height responded very well to wet and dry irrigation treatments in both 1990 (fig. 2c) and 1991 (fig. 2f).

Simulated LAI and canopy weight, height, and width agreed with measured data for the optimum irrigation and optimum N fertilization treatment during the AgIIS experiment (fig. 3). However, the model did not appropriately respond to the low irrigation treatment. This result was likely due to the small irrigation deficit imposed during AgIIS, a difference of only 64 mm between the wet and the dry treatments (table 1). During the 1990 and 1991 FACE studies, irrigation deficits were respectively 130 and 256 mm between the wet and dry treatments, more than twice the deficit imposed during AgIIS. Further evidence of the lower irrigation deficit is apparent in the canopy weight measurements

Table 4. Measured and simulated cotton development.[a]

Development	FACE 1990		FACE 1991		AgIIS 1999		FISE 2002		FISE 2003	
Stage	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
Emergence	3 May	2 May	26 Apr.	26 Apr.	27 Apr.	27 Apr.	2 May	1 May	25 Apr.	26 Apr.
First Flower	6 July	7 July	6 July	6 July	8 July	7 July	9 July	9 July	6 July	5 July
Maturity	18 Sept.	17-18 Sept.	17 Sept.	15-18 Sept.	22 Sept.	21 Sept.	21 Sept.	24 Sept.	18 Sept.	20 Sept.

[a] AgIIS = Agricultural Irrigation Imaging System, FACE = free-air carbon dioxide enrichment, FISE = FAO-56 irrigation scheduling experiment, Meas. = measure, and Sim. = simulated.

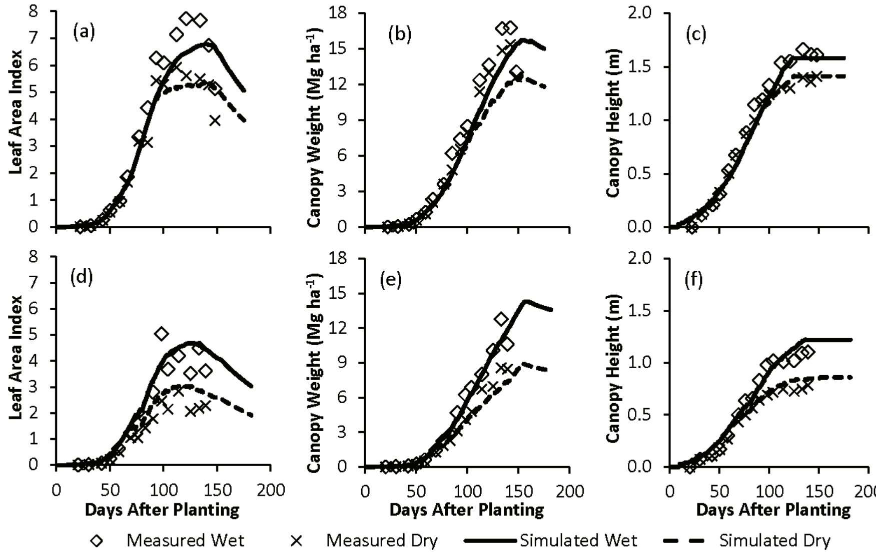

Figure 2. Measured and simulated leaf area index, canopy weight, and canopy height for wet and dry irrigation treatments with ambient atmospheric carbon dioxide concentrations during the (a to c) 1990 and (d to f) 1991 free-air carbon dioxide enrichment (FACE) experiments.

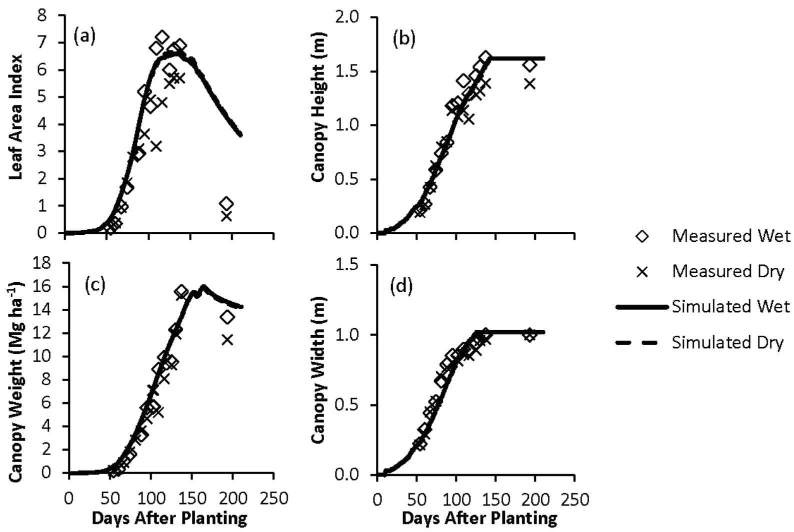

Figure 3. Measured and simulated (a) leaf area index, (b) canopy height, (c) canopy weight, and (d) canopy width for wet and dry irrigation treatments with optimum nitrogen management during the 1999 Agricultural Irrigation Imaging System (AgIIS) experiment.

(fig. 3c), with a difference of only 325 kg ha^{-1} (2%) between maximum measurements for the wet and dry treatments. Measured responses of LAI and canopy height to the irrigation treatments were evident (figs. 3a and 3b), but the model did not simulate these responses. Thus, subtle differences in irrigation management may not elicit a substantial difference in model response.

Crop Growth Responses to Fertilization

Although the model did not respond to the irrigation treatments imposed during AgIIS (fig. 3), its response to the optimum and low N fertilization treatments was clear (fig. 4). As a result of N deficits, the model simulated an N stress response beginning 101 DAP for the low N treatment, and this response continued through the end of the growing season. Nitrogen stress effects on the LAI simulation were apparent immediately after the N deficits were simulated (fig. 4a). Due to feedbacks from reductions in simulated LAI, N stress effects on simulated canopy height and canopy weight occurred later (approximately 130 DAP), so the overall effects of N stress on these aspects of the simulation were less than that for LAI. Under both low irrigation (fig. 3d) and low N fertilization (fig. 4d), there was no measured effect of water or N stress on canopy width, and the model also did not simulate a canopy width response in either case. Although these meter stick measurements of canopy width were prone to error, the measurements nonetheless approximate canopy cover. Thus, neither of the imposed water or N deficits were severe enough to prevent canopy closure. This provides evidence that the AgIIS study could perhaps be redesigned for more thorough model testing. The significance of the AgIIS study among those presented herein is that it tested the interaction of both water and N deficits on cotton growth responses, which are the two leading yield-limiting factors in many cropping systems.

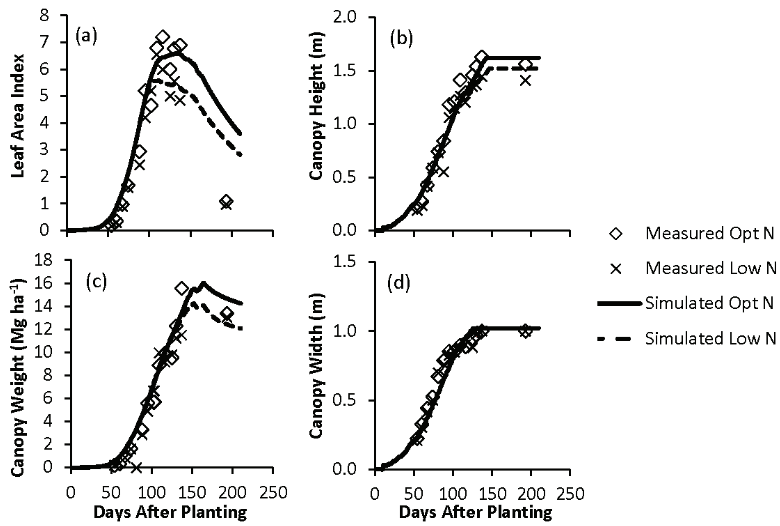

Figure 4. Measured and simulated (a) leaf area index, (b) canopy height, (c) canopy weight, and (d) canopy width for optimum and low nitrogen (N) fertilization treatments with optimum irrigation management during the 1999 Agricultural Irrigation Imaging System (AgIIS) experiment.

Differences between the simulated responses of LAI and canopy weight to high and low N treatments at the typical planting density during the FISE studies were minor (not shown). Thus, the model did not have a substantial response to the N treatments imposed. A number of factors made the FISE data sets poor for testing the model's response to N fertilizer. Foremost, initial soil N data were not collected during the study (table 3). Second, leaf area was not determined from the destructive biomass samples. Therefore, explicit calculations of LAI were not possible. Instead, canopy height and width data were used to calculate the compound vegetation index developed by Scotford and Miller (2004), and LAI was calculated using a regression model developed with similar, unpublished data from a more recent cotton experiment at MAC. As compared to these LAI estimates, the model simulated LAI well for the high N treatment in both years and for the low N treatment in 2002. In 2003, the model overestimated LAI by approximately 1.0 for the low N treatment between 100 and 150 DAP (not shown). The final issue with the FISE data set was that no destructive biomass samples were available as a measure of canopy weight in 2002. In 2003, canopy weight measurements were similar between the high and low N treatments at the typical planting density, as were the simulations. The main objective for the FISE experiments was testing remote sensing methods for irrigation scheduling, and thus it was not the investigators' goal to the collect data required for testing cotton model responses to N fertilizer.

Crop Growth Responses to Planting Density

Simulated responses to the planting density treatments imposed during the FISE experiments were more interesting than that for N fertilizer, albeit the limitations of the FISE data sets for model testing remained. The model overestimated LAI for the densely planted treatment in both years, although the overestimation was worse in 2003 (fig. 5d) than in 2002 (fig. 5a). As described in the previous section, LAI measurements were estimated from canopy height and width, which could be a contributing factor. In addition, the model may have underestimated the effects of competition among plants when the planting density was higher than normal. On the other hand, the LAI of sparsely planted cotton was simulated well in both years. The simulated LAI for the typical planting density (not shown) was approximately midway between that for the dense and sparse treatments. The model simulation of canopy weight was overly unresponsive to planting density, as it generally underestimated canopy weight for the dense treatment and overestimated canopy weight for the sparse treatment in 2003 (fig. 5e). Unfortunately, measurements were not available to verify this result for the 2002 study (fig. 5b). Model responses for canopy height were the opposite of the measurements (fig. 5c and 5f). In both years, the measured final canopy height was lower for the dense treatment than for the sparse treatment. However, the model simulated slightly taller cotton plants for the dense treatment as compared to the sparse treatment, further evidencing that the model did not fully describe the effects of resource competition at the higher planting density. Model simulations for the typical (~11.5 plants m^{-2}, not shown) and sparse treatments (~5.2 plants m^{-2}) were in similar agreement with measured LAI, canopy weight, and canopy height. Simulations for the dense treatment (~22.1 plants m^{-2}) diverged more substantially from measurements.

Crop Growth Responses to Free-Air Carbon Dioxide Enrichment

Simulated responses of LAI, canopy weight, and canopy height responded appropriately to ambient atmospheric [CO_2] and FACE treatments with optimum irrigation management for the 1990 and 1991 FACE studies (fig. 6). As reported by Mauney et al. (1994), LAI was greater for the FACE treatments from 69 to 84 DAP in 1991, and no consistent differences attributable to the FACE environment were observed thereafter. The model simulated slightly higher LAI due to FACE treatments from approximately 75 to 100 DAP in 1991, but LAI simulations for ambient at-

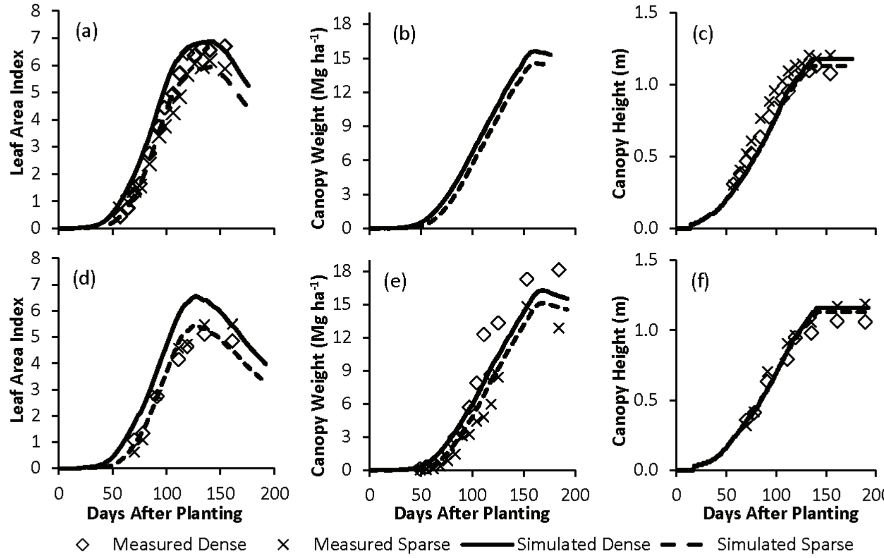

Figure 5. Measured and simulated leaf area index, canopy weight, and canopy height for dense and sparse planting densities with optimum nitrogen fertilizer management during the (a to c) 2002 and (d to f) 2003 FAO-56 irrigation scheduling experiments (FISE).

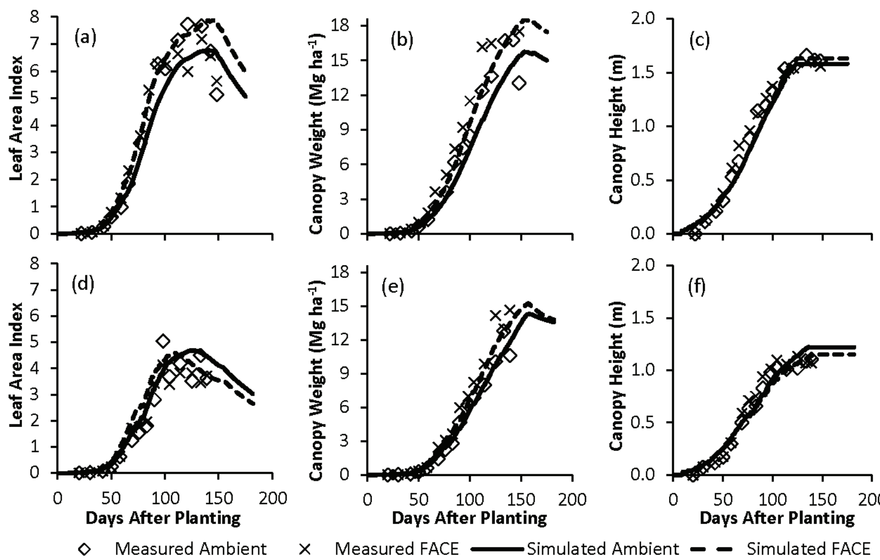

Figure 6. Measured and simulated leaf area index, canopy weight, and canopy height for ambient atmospheric carbon dioxide and free-air carbon dioxide enrichment (FACE) treatments with optimum irrigation management during the (a to c) 1990 and (d to f) 1991 FACE studies.

mospheric [CO_2] were higher in the later season (fig. 6d). The model simulated higher LAI for the FACE environment for most of the 1990 season, although measurements indicated that LAI for ambient atmospheric [CO_2] was higher from 100 to 150 DAP (fig. 6a). Mauney et al. (1994) did not discuss this result or present the 1990 LAI measurements. The model simulated higher canopy weight for FACE treatments as compared to ambient atmospheric [CO_2] for both the 1990 and 1991 studies (figs. 6b and 6e). Measurements also demonstrated significantly higher biomass for FACE treatments as compared to control treatments for most sampling dates in both years (Mauney et al., 1994). Both the simulated and measured differences in canopy height were small for FACE and ambient atmospheric [CO_2] treatments, indicating a minimal effect of [CO_2] on canopy height (figs. 6c and 6d).

Trends in atmospheric [CO_2] are perhaps the most certain evidence of climate change, with measurements of 320 μmol mol^{-1} on Mauna Loa in 1960 that now exceed 400 μmol mol^{-1} (www.esrl.noaa.gov/gmd/ccgg/trends/). Associated changes in the amount and distribution of rainfall and increases in air temperature are also anticipated but are more uncertain at this time. Impacts of potential rainfall changes on crop growth in central Arizona are expected to be minimal because rainfall rarely exceeds 10% of the water required for cotton production, and arid regions are expected to become drier with climate change (Cayan et al., 2010). Available irrigation water will largely determine production potential, not local rainfall. Regional climate change impacts on precipitation in the Colorado River basin, which supplies water to central Arizona, will likely play a role. Although the model responded appropriately to increased atmospheric [CO_2], the model was not evaluated for the effects of increased air temperature because no field experiment or experimental data were available for such testing. Even if there was such a study, the model does not currently simulate transpiration effects on canopy temperature. Since evaporative cooling in arid environments often causes the microclimate of a well-watered crop canopy to be cooler than the surrounding air, calculations of crop development based on air temperature may be flawed. The addition of a complete energy balance routine in the model would permit calculations of temperature within the cotton canopy, which would improve crop development calculations and facilitate model use over a wider range of humidity environments.

CROP YIELD RESPONSES

The RMSE values between measured and simulated seed cotton yield for the 1990 FACE, 1991 FACE, 1999 AgIIS, 2002 FISE, and 2003 FISE studies were 501, 1107, 105, 345, and 188 kg ha^{-1}, respectively (20%, 28%, 3%, 8%, and 4% of mean values). Measured seed cotton yield for all treatments was lower for the 1990 FACE experiment than for the 1991 FACE study (table 5), and 1990 yield values were comparatively lower than that for all of the later studies. This was partly due to the earlier harvest date for the FACE studies (table 1), but model calibration results and yield comparisons with 1991 FACE data highlighted odd cotton growth behavior in 1990. Although the 1990 yields were lower than 1991 yields, measurements of LAI and canopy weight were substantially higher in 1990 as compared to 1991 (fig. 2). Thus, the crop tended to have a more vegetative growth habit in 1990 with detrimental effects on yield. The model was unable to simulate this effect without adjusting the XFRT parameter to simulate lower yield in 1990 as compared to 1991 (table 2). Overall, the model simulated yield poorly for both FACE experiments as compared to the later studies (table 5). The earliness of the yield measurements during the FACE studies likely had a greater impact on these deviations than the model. For example, measured yield was unexpectedly often lower for the wet treatment than the corresponding dry treatment for both FACE studies, whereas the model always simulated higher yield for the wet treatment than for the dry treatment, as would be expected.

For the AgIIS study, the simulated yields matched measurements better than those for the other studies. However, due to Lygus infestation in the later 1999 growing season and the habit of Lygus to differentially select healthy cotton bolls (Willers et al., 1999), it is unclear whether the yield measurements were representative of the treatments imposed during the AgIIS study. For example, yield measurements for the low N treatment were larger than for the optimum N treatment (table 5), while the opposite response occurred for canopy weight and LAI (fig. 4). Lygus may have differentially selected the high N treatment plots, resulting in lower yield for those treatments. The model was able to simulate this yield response when the XFRT and THRSH parameters were adjusted to compensate for low yields (table 2); however, no effect of Lygus pressure was included in the simulation. Thus, adjustment of XFRT and THRSH to lower boll growth potential may have affected simulated cotton growth processes similarly to actual growth responses due to Lygus pressure.

For the FISE studies, yield simulations were variable depending on the treatment. For the 2002 experiment, simulated yields for the dense treatment were overestimat-

Table 5. Measured and simulated seed cotton yields and total seasonal evapotranspiration with absolute and percent errors between measured and simulated values.[a]

Experiment	Treatment	Seed Cotton Yield Meas. (kg ha^{-1})	Seed Cotton Yield Sim. (kg ha^{-1})	Seed Cotton Yield Abs. Err. (kg ha^{-1})	Seed Cotton Yield % Err. (%)	Evapotranspiration Meas. (mm)	Evapotranspiration Sim. (mm)	Evapotranspiration Abs. Err. (mm)	Evapotranspiration % Err. (%)
FACE 1990	Ambient [CO_2], wet	1388	2277	+889	+64	993	974	-19	-2
	Ambient [CO_2], dry	2206	2078	-128	-6	901	892	-9	-1
	FACE wet	3031	3042	+11	+0	982	989	+7	+1
	FACE dry	3153	2712	-441	-14	887	904	+17	+2
FACE 1991	Ambient [CO_2], wet	2756	4435	+1679	+61	971	965	-6	-1
	Ambient [CO_2], dry	3097	2643	-454	-15	754	752	-2	+0
	FACE wet	5042	5153	+111	+2	953	959	+6	+1
	FACE dry	4692	3326	-1366	-29	742	764	+22	+3
AgIIS 1999	Wet, high N	3134	3339	+205	+7	926	921	-5	-1
	Wet, low N	3508	3506	-2	+0	913	918	+5	+1
	Dry, high N	3250	3216	-34	-1	860	923	+63	+7
	Dry, low N	3479	3509	+30	+1	860	916	+56	+7
FISE 2002	Dense plants, high N	3661	4392	+731	+20	958	992	+34	+4
	Dense plants, low N	3997	4341	+344	+9	966	989	+23	+2
	Typical density, high N	4220	4389	+169	+4	968	955	-13	-1
	Typical density, low N	4348	4290	-58	-1	949	952	+3	+0
	Sparse plants, high N	4335	4375	+40	+1	963	908	-55	-6
	Sparse plants, low N	4402	4232	-170	-4	944	906	-38	-4
FISE 2003	Dense plants, high N	4926	4861	-65	-1	1048	1107	+59	+6
	Dense plants, low N	4254	4356	+102	+2	1063	1103	+40	+4
	Typical density, high N	5205	4846	-359	-7	1069	1071	+2	+0
	Typical density, low N	4337	4314	-23	-1	1043	1065	+22	+2
	Sparse plants, high N	4576	4812	+236	+5	1057	1024	-33	-3
	Sparse plants, low N	4424	4314	-110	-2	1057	1015	-42	-4

[a] AgIIS = Agricultural Irrigation Imaging System, [CO_2] = carbon dioxide concentration, FACE = free-air carbon dioxide enrichment, FISE = FAO-56 irrigation scheduling experiment, Meas. = measured, Sim. = simulated, Abs. Err. = absolute error, and % Err. = percent error.

Table 6. Statistical tests to assess ability of CSM-CROPGRO-Cotton to explain within-experiment variation in seed cotton yield and evapotranspiration.[a]

Test	r^2	F	RSE	p-Value
Seed cotton yield				
Experiments (eq. 3)	0.65	8.73	611.1	0.00***
Experiments + simulations (eq. 4)	0.72	9.21	560.7	0.00***
ANOVA RSE (eqs. 3 and 4)	-	4.57	-	0.05*
Evapotranspiration				
Experiments (eq. 3)	0.67	9.5	56.0	0.00***
Experiments + simulations (eq. 4)	0.91	34.6	30.6	0.00***
ANOVA RSE (eqs. 3 and 4)	-	45.6	-	0.00***

[a] ANOVA = analysis of variance, LM = linear regression model, and RSE = residual sum of square error.

ed at both the high and low N rate (table 5), while yield simulations at the lower planting densities were in better agreement with measurements. For the 2003 experiment, simulated yield for the low N treatment were in better agreement with measurements as compared to yield simulations for the high N treatment at the typical and sparse planting densities. Overall, yield simulation errors were small for FISE, but the XFRT parameter was adjusted higher for 2003 FISE as compared to the other studies to simulate yield accurately (table 2). This could indicate that the yield data were recorded as wet weights.

Comparing the statistical results between the first (eq. 3) and second (eq. 4) linear regression models for seed cotton yield, the coefficient of determination (r^2) increased by 0.07 from 0.65 to 0.72 and the residual sum of squared error decreased by 50.4 kg ha^{-1} (1.3% of mean values) from 611.1 kg ha^{-1} (16.0% of mean values) to 560.7 kg ha^{-1} (14.7% of mean values) (table 6). An analysis of variance subsequently demonstrated a significant reduction in residual sum of squared error when comparing the two regression models. Therefore, in spite of the previously described issues with the measured yield data, CSM-CROPGRO-Cotton was statistically able to simulate seed cotton yield responses to the imposed experimental treatments, independent of the variability due to seasonal factors ($p < 0.05$). However, substantial adjustments of the XFRT and THRSH parameters were required to achieve this result (table 2).

Evapotranspiration Responses

The RMSE values between measured and simulated total seasonal ET for the 1990 FACE, 1991 FACE, 1999 AgIIS, 2002 FISE, and 2003 FISE studies were 14, 12, 42, 33, and 38 mm, respectively (1%, 1%, 5%, 3%, and 4% of mean values). While the model was comparatively poorer at simulating yield for the FACE studies, simulations of ET were best for the FACE studies. The model responded appropriately to the dry irrigation treatment with ambient atmospheric [CO_2] in both 1990 and 1991, simulating ET within 10 mm of measured (table 5). Simulations of ET for the dry FACE treatments were overestimated by more than 15 mm in both years, although the model responded well among the wet and dry FACE treatments. For the AgIIS study, the model simulated ET accurately for low and high N rates under optimum irrigation. However, larger discrepancies between measured and simulated ET were found for simulations at the low irrigation rate. For both FISE studies, ET simulation errors were most prominent among the planting density treatments. The model overestimated ET for the dense planting, likely due to simultaneous overestimation of LAI (fig. 5). The ET simulations for the sparse treatment were underestimated by the model. At the typical planting density, ET simulations were reasonable in both 2002 and 2003.

Comparing the statistical results between the first (eq. 3) and second (eq. 4) linear regression models for ET, the coefficient of determination (r^2) increased by 0.24 from 0.67 to 0.91 and the residual sum of squared error decreased by 25.4 mm (2.7% of mean values) from 56.0 mm (5.9% of mean values) to 30.6 mm (3.2% of mean values) (table 6). An analysis of variance subsequently demonstrated a significant reduction in residual sum of squared error when comparing the two regression models. Therefore, CSM-CROPGRO-Cotton was able to simulate ET responses to the imposed experimental treatments, independent of the variability due to seasonal factors ($p < 0.05$). Overall, ET simulations responded appropriately to the experimental treatments imposed during these field studies.

These ET simulation results (table 5) and the EORATIO parameterization results (table 2) support the changes to the model's ET calculation in the present study: computing ET_o using the ASCE Standardized Reference Evapotranspiration Equation (Walter et al., 2005) and using the DeJonge et al. (2012) approach to calculate K_c as a function of LAI (eq. 1). Substantial differences in ET calculations were found when the new ET approach was compared with two older methods in the CSM: the Priestley-Taylor method (option P) and the original FAO-56 approach (option F). Reference ET (ET_o) with the original FAO-56 option in the model was often more than 200 mm less than that from the ASCE approach (table 7). Although both approaches were based on the Penman-Monteith equation, slight deviations in calculation approaches for the psychrometric constant, net radiation, and the slope of the saturation vapor pressure-temperature curve were found. In addition, the ASCE

Table 7. Comparison of total seasonal measured evapotranspiration (ET) with simulated reference ET (ET_o), potential ET (PET), and actual crop ET (ET_c) using three ET simulation options in the DSSAT Cropping System Model. Data are presented for the most standard treatment in each of the five cotton experiments simulated in this study.[a]

	Measured	Priestley-Taylor			Original FAO-56			New ASCE/DeJonge et al. (2012)		
Experiment	ET (mm)	ET_o (mm)	PET (mm)	ET_c (mm)	ET_o (mm)	PET (mm)	ET_c (mm)	ET_o (mm)	PET (mm)	ET_c (mm)
FACE 1990	993	-	1012	999	791	924	916	990	982	974
FACE 1991	971	-	1132	839	849	956	814	1126	1053	965
AgIIS 1999	926	-	942	838	756	904	845	891	965	921
FISE 2002	968	-	990	856	764	914	832	964	1020	955
FISE 2003	1069	-	1181	998	909	1066	961	1145	1145	1071

[a] AgIIS = Agricultural Irrigation Imaging System, FACE = free-air carbon dioxide enrichment, and FISE = FAO-56 irrigation scheduling experiment.

method uses predefined constants for the aerodynamic resistance terms, whereas the FAO-56 approach in the model calculates these terms explicitly. With such differences in ET_o calculations, it is not surprising that Thorp et al. (2010) required unrealistically high EORATIO values (maximum K_c = 1.8) with the original FAO-56 approach to simulate ET appropriately for Arizona wheat. Use of the EORATIO values calibrated herein (table 2) with the older FAO-56 method thus resulted in lower PET and actual ET as compared to the newer ASCE method (table 7), and the FAO-56 method underestimated actual ET from 77 to 157 mm (8% to 16%) as compared to measurements. Likewise, the Priestley-Taylor approach underestimated actual ET up to 132 mm (14%) as compared to measurements. This is not surprising since the Priestley-Taylor method ignores relative humidity and wind speed measurements, makes no assumptions about a reference crop, and calculates no ET_o. Such discrepancies in ET simulation methods could potentially have drastic effects on simulation output, especially since the deviations were similar in magnitude to the irrigation deficits imposed in some of the field studies (table 1). Future studies should more fully evaluate and compare these ET simulation methods for other crops and environments.

The results highlight the value of the standardized approach to calculate ET_o in crop models, as different approaches can lead to drastically different ET simulations. Even when two approaches are rooted in Penman-Monteith, differences can arise due to assumptions made in implementing the required equations. The ASCE Standardized Reference Evapotranspiration Equation is now well accepted in the ET research community and is the official approach for reporting ET_o at meteorological network stations in Arizona (Brown, 2005) and elsewhere in the U.S. Its use in cropping system models would better align simulation studies with other ET research efforts and facilitate model intercomparisons. While the modification to the model's K_c calculation by DeJonge et al. (2012) is appropriate for use with the ASCE Standardized Reference Evapotranspiration Equation, their study did not acknowledge the deviations in ET_o calculations between the model's original FAO-56 option and the newer ASCE method, and the details of their ET_o calculation approach are unclear. Because K_c and ET_o together estimate PET (eq. 2), it is necessary to evaluate K_c and ET_o methods collectively. Establishing agreement on a standardized ET_o calculation method provides a basis for objectively comparing different approaches to calculate K_c as a function of LAI or other model state variables. Although the ET simulations in the present study were favorable using the DeJonge et al. (2012) method, further effort is warranted to ensure that the method is consistent with other aspects of the simulation model, particularly the partitioning of PET to potential soil evaporation and potential plant transpiration. Unlike ET_o, the calculation of K_c within a crop growth model necessarily deviates from the standard ASCE (Walter et al., 2005) and FAO-56 (Allen et al., 1998) methods because K_c must be calculated dynamically from simulated crop growth variables rather than explicitly defined. Crop modelers must therefore determine the appropriate approach for K_c calculation within their model, while including an option for the ASCE Standardized Reference Evapotranspiration Equation would offer greater uniformity in ET_o calculations among models, simulation studies, and research groups.

Data for Model Evaluation

The availability of data sets from several different field studies permitted a unique evaluation of CSM-CROPGRO-Cotton in this study. One advantage was that the data limitations of one field study could be offset by the strengths of a different data set. Thousands of dollars and many hours of labor were invested to complete the field investigations, yet none of them provided data to test all of the model components that were evaluated herein. By combining information from multiple studies, a more thorough model evaluation could be conducted. One weakness of this approach was the wide variability in protocols for data collection, processing, archiving, and documentation among the various researchers involved in the field studies. Prior to model evaluation, a substantial effort was required to assess data availability and quality for each field study (table 3). Model calibration efforts and comparisons of measured and simulated data also often guided suspicions about data quality. The measured seed cotton yield data were the best example of this, and efforts are needed to improve seed cotton yield measurement techniques for use in cropping system model evaluation. Finally, although great investments were made to conduct each field study, none had a primary objective to provide data for evaluation of crop models. In addition to critical omissions of key measurements, choices for experimental design weakened the utility of some data sets for model testing purposes. For example, the AgIIS study did not impose a high enough irrigation deficit for thorough testing of the model's response to water. In addition, no experiments tested cotton growth and development responses to planting date, which would permit evaluation of simulated responses to temperature and photoperiod. Because field experiments require large investments of time and labor, crop simulation models should be used as a design tool to establish effective treatments for field testing as well as an analysis tool for evaluation and assessment of field experimental results.

Conclusions

CSM-CROPGRO-Cotton responded appropriately to a variety of management and climate change factors, including irrigation rates, N fertilization rates, planting densities, and FACE, in the arid environment of central Arizona. The model's ET routines were modified to calculate ET_o using the ASCE Standardized Reference Evapotranspiration Equation with K_c calculations based on the DeJonge et al. (2012) approach. These changes were essential to simulate ET reasonably for the arid conditions of the study site while maintaining realistic values for the EORATIO parameter, which mimics maximum K_c in the model. Next steps will be to evaluate the new ET routine for other crops and environments and to test the CSM-CROPGRO-Cotton model for real-time cotton irrigation scheduling in Arizona.

Other aspects of the simulation model were shown to respond appropriately without modification to the model. The model simulated lower LAI and canopy weight in response to water and N deficits, although the deficits imposed during some experiments were not substantial enough for thorough model testing. The model generally responded well for typical and sparse planting densities, but greater deviations between measured and simulated LAI, canopy weight, seed cotton yield, and ET were found for the dense cotton treatment. Further investigation into the model's response to planting density is therefore warranted but is likely not an issue unless non-standard planting densities are required for a particular application. Methodologies for simulating defoliation and associated impacts on cotton growth and maturity could also be made more straight-forward in the model, especially since this is a common management practice in cotton production. With regard to global climate change, the results of this study demonstrated appropriate simulated responses of LAI and canopy weight to increased atmospheric [CO_2], as imposed during the FACE studies. However, the model was not evaluated for the effects of increased air temperature, which is also anticipated with climate change, because experimental data were not available for such testing. Efforts to collect such data and efforts to improve simulations of the canopy microclimate by adding a complete energy balance routine to the model are recommended.

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