ADAPTING THE CROPGRO-COTTON MODEL TO SIMULATE COTTON BIOMASS AND YIELD UNDER SOUTHERN ROOT-KNOT NEMATODE PARASITISM

B. V. Ortiz, G. Hoogenboom, G. Vellidis, K. Boote, R. F. Davis, C. Perry

ABSTRACT. *Cotton (*Gossypium hirsutum *L.) yield losses by southern root-knot nematode (RKN;* Meloidogyne incognita *(Kofoid & White) Chitwood) are usually assessed after significant damage has been caused. However, estimation of potential yield reduction before planting is possible by using crop simulation. The main goal of this study was to adapt the Cropping System Model (CSM)-CROPGRO-Cotton for simulating growth and yield of cotton plants infected with RKN. Two hypotheses were evaluated to simulate RKN damage: (1) RKN acting as a sink for soluble assimilate, and (2) RKN inducing a reduction of root length per root mass and root density. The model was calibrated and adapted using data collected in an experiment that was conducted in 2007 and was part of a long-term crop rotation study. The experiment had a split-plot design, replicated six times, with drought stress levels assigned to the main plots and fumigation levels assigned to the subplots. The model was evaluated with seed cotton weight data collected in an experiment that was conducted in 2001 and was part of the same long-term crop rotation experiment. The fumigation treatments created various levels of RKN population densities. The model was adapted by coupling the RKN population to the removal of daily assimilates and decreasing root length per unit mass. The assimilate consumption rate was obtained after minimizing the error between simulated and observed biomass and yield components for the limited drought stress, non-fumigated treatment. Different values of root length per unit root weight (RFAC1) were used to account for early symptoms of RKN damage on leaf area index (LAI) and vegetative biomass under the non-fumigated, drought stress conditions. After model adaptation, the simulations indicated that LAI, total biomass, boll weight, and seed cotton decreased with elevated RKN population. The impact of RKN was more pronounced under severe drought stress. The lowest RMSE of LAI simulations occurred for the non-fumigated treatments under medium and severe drought stress (0.71 and 0.65 m^2 m^{-2}, respectively). Biomass was simulated with a prediction error within a range of 6% to 18.4% and seed cotton within a range of -11.2% to 2.7%. Seed cotton weight losses associated with RKN infection increased with the level of drought stress (9%, 20%, and 18% for the low, medium, and severe drought stress). Model evaluation showed that seed cotton weight was slightly more overpredicted for the fumigated than for the non-fumigated treatments, with prediction errors of 28.2%, 15.8%, and 2.0% for the low, medium, and severe drought stress, respectively. Similar to the calibration of the model, the yield losses increased with the combination of RKN and drought stress (20% and 29% for the low and severe drought stress). The results showed the potential for using the CSM-CROPGRO-Cotton model to account for RKN damage as well as to simulate yield reduction. However, further model evaluation might be needed to evaluate the values of assimilate consumption and root length per unit weight for different environmental conditions and management practices.*

Keywords. *Cotton, Crop models, Drought stress, DSSAT, Southern root-knot nematode, Yield losses.*

Southern root-knot nematode (RKN; *Meloidogyne incognita* (Kofoid & White) Chitwood) is considered the most harmful plant-parasitic roundworm for cotton (*Gossypium hirsutum* L.) production in the U.S. (Koenning et al., 2004). The greatest yield losses attributed to nematode pressure across the U.S. cotton belt occurred in the period 1987-2000, when damage increased from 1.0% to 4.39% (NCC, 2008). In Georgia, the third largest upland cotton producer in the U.S. (USDA, 2008), losses due to nematodes in 2007, 75% associated with RKN, totaled $50.2 million (UGA, 2007). A survey carried out between 2002 and 2003 showed that major cotton-producing counties had RKN populations that were above the threshold (100 second-stage juveniles of RKN per 100 cm^3 of soil; Davis et al., 1996), which indicated that cotton producers lost approximately 77,000 bales of cotton annually due to RKN damage (Blasingame and Patel, 2001; Kemerait et al., 2004).

Several metabolic and physiologic changes in cotton plants are associated with RKN parasitism. The galls or root-knots, which develop in the cotton root system as a result of root feeding, are considered to be metabolic sinks of assimilates (CH_2O) (McClure, 1977; Williamson and Gleason, 2003), causing a change in partitioning expressed as a reduction in above-ground cotton biomass. The combination of assimilate translocation by the roots and physiological changes

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(e.g., water and nutrients flow reduction, low stomatal conductance, reduction in the transpiration rate and photosynthesis) explains the above-ground symptoms described as chlorosis, stunting, inhibition of leaf expansion, and an increase of root/shoot ratio that are mainly detected after damage has occurred (Kirkpatrick et al., 1991; Kirkpatrick et al., 1995; Wallace, 1987; Wilcox-Lee and Loria, 1987). Zhang et al. (2006) found that the root systems of susceptible genotypes were smaller than resistant genotypes, which had much larger plants and root mass. Khoshkhoo et al. (1994) associated high levels of glucose in leaves of susceptible cotton genotypes with a reduction of root mass due to RKN feeding. A decrease in yield and yield components (e.g., fiber length, seed cotton, lint percentage, and boll weight) as well as root mass and length are also some of the impacts of RKN infection (Colyer et al., 1997; Davis and May, 2005).

During the last decade, crop models have been used extensively in agriculture to simulate crop responses to different abiotic factors. The Cropping System Model (CSM)-CROPGRO-Cotton model is part of the suite of crop simulation models that encompass the Decision Support System for Agrotechnology Transfer (DSSAT; Jones et al., 2003; Hoogenboom et al., 2004). The model simulates growth, development, and yield of cotton for different weather and soil conditions and management practices. Leaf, stem, root, shell, and seed mass are computed on a daily basis, as well as growth stages, leaf area index (LAI), root length density and depth, soil water availability, and soil water content for different soil layers. Computer models have also been used to simulate the potential effects of pest damage on a crop, but on a limited basis, classifying pest damage as stand reducers, photosynthetic rate reducers, leaf senescence accelerators, light stealers, tissue consumers, assimilate sappers, and turgor reducers (Boote et al., 1983). Pest damage and its effects can be simulated with crop models by coupling pest population density or specific damage type, expressed in percentage or rate basis, to state variables such as leaf, stem, seed, shell, or root mass; LAI; as well as photosynthetic rate or rate of tissue senescence (Teng et al., 1998; Batchelor et al., 1992). Different crop models and simulation strategies have been used to quantify the effects of pests and diseases on crops. For instance, the CROPGRO-Soybean model was used to simulate soybean cyst nematode (SCN) parasitism through various strategies: reduction of water uptake from damaged roots due to an increment of carbon allocation to roots in the model (Boote et al., 1983), coupling damage of various levels of SCN population to daily photosynthesis and root water uptake to simulate yield reduction (Fallick et al., 2002). Paz et al. (2001) also used the CROPGRO-Soybean model to quantify yield losses associated with SCN parasitism.The SOYGRO model was used by Batchelor et al. (1992) to simulate the effects of soybean defoliation caused by velvetbean caterpillar (*Anticarsia gemmatalis*). They coupled weekly data of the cumulative defoliation levels to leaf area through the cumulative leaf damage variable (LAID). Pinnschmidt et al. (1995) used the CERES-Rice model to couple the damage effects of defoliators, weed competition, and leaf blast / sheath blight diseases. Naab et al. (2004) evaluated the CROPGRO-Peanut model to simulate peanut yield losses associated with the late leafspot disease (*Cercosporidium personatum*) using leaf defoliation data.

Although the CSM model provides options to simulate cotton growth and development and yield as influenced by the environment and agronomic practices, few attempts have been made to simulate the potential effects of RKN population levels on cotton growth, development, and yield. The impact of RKN population densities on different cotton plant components and the interaction with different soil types and weather are still not well understood. Therefore, the CSM-CROPGRO-Cotton model offers the opportunity to simulate scenarios of different RKN damage levels to help guide the definition of the most effective RKN management strategies for different production areas.

The main goal of this study was to adapt the Cropping System Model (CSM)-CROPGRO-Cotton for simulating growth and yield of cotton plants infected with RKN. Specific objectives were to evaluate two different hypotheses relating to simulation of RKN damage: the first hypothesis was that RKN acts as sink of soluble assimilate, and the second hypothesis was that RKN induces a reduction of root length per root mass and root density.

MATERIALS AND METHODS

EXPERIMENTAL FIELD

Data collected in 2007 from a long-term study conducted at the Gibbs Farm of the University of Georgia in Tifton, Georgia (31° 26′ 24 ″ N, -83° 34′ 47.9 ″ E; 90 m elevation above mean sea level) were used for model calibration and adaptation. The goal of this experiment was to study the differences in cotton (*Gossypium hirsutum* L.) biomass and yield caused by high population of RKN and the interaction of RKN population with drought stress. The soil type at the experimental site was a Tifton loamy sand (fine, loamy, siliceous, thermic Plinthic Paleudults) with an approximate depth of 2.0 m depth. The experiment, with a split-plot design replicated six times, consisted of six treatments as a factorial combination of three drought stress levels (main plots): low (1), medium (2), and high drought stress (3); and two fumigation levels (subplots): non-fumigated (-) and fumigated (+) with 1,3-dichloropropene at 65 L ha^{-1} (Telone II, Dow AgroSciences, Indianapolis, Ind.). Fumigation levels were used to create different levels of RKN population densities. Irrigation volume and frequency were selected to create the three levels of drought stress. Each plot or experimental unit consisted of four 15.2 m rows spaced at a distance of 91 cm. The cotton cultivar Delta & Pineland (DPL) 458 Boll-Guard, Roundup-Ready cotton (DP 458 BG/RR) was planted on 11 May 2007. The same variety has also been grown during the previous seven years in this field. Seeds were sown at a depth of 1.2 cm depth, and plants were thinned to a density of 14 plants per m^2.

Prior to planting, the field was disk-plowed and harrowed, and hairy vetch, which was the winter cover crop, was incorporated into the soil. The experiment was fertilized two days prior to sowing with NPK (0-20-20, 392 kg ha^{-1}), and nitrogen (114 kg ha^{-1}) was applied approximately one month after planting.

SOIL DATA

The soil type of the experimental site was classified as Tifton loamy sand (table 1) by Perkins et al. (1986). To compare this classification with local field data, soil cores up to a depth of 90 cm were collected at the center of the 36 experimental plots for soil type and texture verification. Each core was divided into four sections (0-15, 15-30, 30-60, and 60-90 cm), and the soil texture of each soil sample was determined by the Bouyoucos hydrometer method (Bouyoucos, 1936; Day, 1965) and compared with the values reported by Perkins et al. (1986).

Soil water tension was monitored with Watermark sensors in the plots of the control treatment (1+, low drought stress, fumigated). The Watermark sensors were installed at three depths (20, 40, and 60 cm) and recorded soil water tension every 2 h on a daily basis using the sensor array design developed by Vellidis et al. (2008). Soil water retention curves (SWRC), derived by Perkins et al. (1986) at four different depths for the Tifton loamy sand, were used to convert soil water tension readings into volumetric soil water content.

Biomass, LAI, and Nematode Population Measurements

Biomass samples were collected at 74, 108, and 132 days after planting (DAP) and at final harvest at 160 DAP. For the first three samples, 1 m of row (0.914 m^2) was harvested from the central rows of each plot. At final harvest, two 1 m rows (1.828 m^2) were harvested. From each biomass sample, a three-plant subsample was separated into leaves, stems plus petioles, closed and open bolls, lint plus seed (seed cotton), and shells. All plant material, including the subsample, was oven dried at 70°C to constant weight. LAI was measured with an LAI-2000 plant canopy analyzer (Li-Cor, Lincoln, Neb.) every two weeks at four different locations within each plot.

Soil samples for RKN population density determination were collected from each experimental plot four times during the growing season at 18, 65, 127, and 172 DAP. The soil samples consisted of a composite sample of 8 to 10 cores per plot that were collected from the root zone. The core had a 3 cm diameter opening and was approximately 20 cm long. Second-stage juveniles (RKN-J2) were extracted from 150 cm^3 of each soil sample by centrifugal flotation (Jenkins, 1964). Nematode counts were then converted into population on a soil volume basis using equation 1:

$$\text{TRKN} = \text{MRKN} * \text{MV}/\text{SV} \qquad (1)$$

where TRKN is the total RKN-J2 population, MRKN is the mean population of RKN-J2 in the soil sample, MV is the volume of soil in the area of 1 m^2 to the sampling depth of 15 cm (150,000 cm^3), and SV is the volume of one subsample (150 cm^3).

Model Calibration

Data collected from the control treatment (1+, low drought stress, fumigated) over six replications were used to calibrate the CSM-CROPGRO-Cotton model. This calibration helped ensure that the constants and response functions that were used in the model were correct and that the model performed well in simulating the growth and yield under the specific environmental conditions (Hunt and Boote, 1998).

Soil Water Holding Characteristics

Because soil water content was estimated at depths of 20, 40, and 60 cm, the volumetric soil water was simulated for the conditions of soil layers 15 to 30 cm, 30 to 45 cm, and 45 to 60 cm deep. The properties that are required by the model for each soil horizon include permanent wilting point or lower limit of plant extractable soil water (LL, $cm^3\ cm^{-3}$), field capacity or drained upper limit (DUL, $cm^3\ cm^{-3}$), saturated water content (SAT, $cm^3\ cm^{-3}$), saturated hydraulic conductivity (KSAT, cm h^{-1}), and a soil root growth factor (SRGF). These properties were initially estimated with the SBuild program of DSSAT Version 4.0 (Hoogenboom et al., 2004). The soil water characteristics were then calibrated using a preliminary set of cultivar coefficients. The volumetric soil water measured between 0 and 60 cm soil depth from the control treatment was used to adjust two soil water characteristics (LL and DUL) in order to match the simulated values to observed values and to make them more specific for the conditions of the experimental field. The LL soil moisture for the first four horizons was initially replaced by a value of 0.67 of the moisture at 100 kPa soil water tension extracted from the SWRC derived from observed values. This value was later adjusted if the simulated water content did not match the lowest observed water content during the soil drying cycles. The values of DUL were adjusted for the first three horizons by analyzing changes in water content with time after rain or irrigation events. Constant soil water content for three days after wetting was selected as the DUL value. Because the DUL was modified according to measured values, the SAT was set as the volumetric soil water content measured at 0.4 kPa soil water tension from SWRC derived from the study by Perkins et al. (1986). The values of soil albedo (0.13), soil drainage (0.6), and runoff curve number (76) were calculated with the SBuild program from data for soil color and drainage, slope, and potential runoff for the Tifton soil. The soil parameters selected were those that minimized the root mean square error (RMSE) between simulated and observed volumetric soil water content for each soil depth of the control treatment.

Cultivar Coefficients

The cultivar coefficients database within the CSM-CROPGRO-Cotton model lacked cultivar DP 458 BG/RR, so coefficients from a similar cotton cultivar were used as a basis to calibrate the coefficients characterizing phenology, as well as vegetative and reproductive growth traits. Sensitivity analyses for phenology dates as well as biomass components (LAI, leaf weight, stem-petiole weight), yield (seed cotton weight), and yield components (boll weight, bolls m^{-2}, seed m^{-2}) were conducted to estimate the appropriate values of the cultivar coefficients that minimized the RMSE between the simulated and observed values of the control treatment.

A modification of the soil fertility factor (SLPF) was also considered when calibrating biomass accumulation, as this factor affects crop growth rate through a modification of daily canopy photosynthetic rate. Model calibration of cultivar coefficients was conducted after the calibration of the soil water holding characteristics.

Model Adaptation

After calibration of the soil properties and cultivar coefficients, the CSM-CROPGRO-Cotton model was adapted to account for RKN damage by: (1) coupling RKN population levels to daily assimilate (g $CH_2O\ m^{-2}\ d^{-1}$) available for growth and respiration, and (2) reducing the root length per root weight.

Assimilate Consumption by RKN

For each treatment, the daily changes of RKN-J2 population throughout the season were calculated by the model from interpolation of the average RKN-J2 population measured four times during the growing season. In this study, it was assumed that each RKN-J2 count reduced assimilates by the same amount.

The daily assimilative consumption expressed as C loss (ASMDOT, g CH_2O m^{-2} d^{-1}) was calculated in the CSM-CROPGRO-Cotton model by equation 2 as:

$$\text{PGAVL} = \text{PGAVL} - \text{ASMDOT} \tag{2}$$

where PGAVL is total available CH_2O available for growth and respiration (g CH_2O m^{-2}), and ASMDOT is the daily assimilative damage (g CH_2O m^{-2} d^{-1}).

Initially, it was assumed that the daily rate of consumption was 0.0016 g juveniles^{-1} d^{-1} based on the consumption rates from other pests that are included in the DSSAT database. Using sensitivity analyses with the low drought stress, non-fumigated treatment (1-), this daily rate was modified to identify the daily rate of assimilate consumption by the RKN-J2 population that minimized the error between simulated and observed biomass, bolls, and seed cotton weight.

Root Length per Unit Root Weigh

In the CSM-CROPGRO-Cotton model, a reduction in the root length per unit root weight (RFAC1) as a consequence of RKN damage will decrease plant-extractable soil water, root density over the soil profile (RLINIT), and new root growth (eqs. 3 and 4). Therefore, processes such us nutrient uptake, water flow to above-ground biomass, transpiration, and growth, among others, will be impacted, resulting in a decrease of yield and total biomass. The RLINIT can be expressed by:

$$\text{RLINIT} = \text{WTNEW} * \text{FRRT} * \text{PLTPOP} * \text{RFAC1} * \text{DEP}/(\text{RTDEP} * 10000) \tag{3}$$

where

RLINIT = initial root density (cm root cm^{-2} ground)
WTNEW = initial weight of the seed or seedling (g $plant^{-1}$)
FRRT = daily fraction of vegetative tissue growth that is allocated to the roots (g root g^{-1} veg)
RFAC1 = root length per unit root weight (cm root g^{-1})
RTDEP = total rooting depth (cm)
PLTPOP = plant population (plants m^{-2})
DEP = cumulative soil depth (cm).

Changes in the root length per unit mass (RFAC1) also impacted the new root growth density (RLNEW), which was calculated as:

$$\text{RLNEW} = \text{WRDOTN} * \text{RFAC1} / 10000 \tag{4}$$

where

RLNEW = daily new root growth (cm root cm^{-2} ground d^{-1})
WRDOTN = dry weight growth rate of new root tissue including N but not C reserves (g root m^{-2} ground d^{-1})
RFAC1 = root length per unit root weight (cm root g^{-1}).

Because the assimilate consumption depends on the population of RKN-J2 extracted from the soil after root damage has been caused, reductions in leaf biomass that occurred early in the growing season may not be entirely accounted for. Therefore, the reduction in root mass and root density through modifications of the RFAC1 could account for early symptoms of low LAI and vegetative biomass by RKN damage.

MODEL EVALUATION AND STATISTICAL METHODS FOR PERFORMANCE ASSESSMENT

Model performance for the cultivar coefficients for the variety 458 BG/RR and the model adaptation for RKN damage were evaluated with seed cotton weight data collected from the experiment that was conducted in 2001. The 2001 and 2007 data were both part of the same long-term crop rotation experiment, but they were considered independent as the experiments were exposed to different weather conditions. The deviation of predicted phenology, biomass at harvest, maximum LAI, seed cotton, and volumetric soil water content at various depths from the observed values were evaluated using three statistical parameters: root mean square error (RMSE), relative error (RE), and index of agreement (*d*; Willmott, 1982). The time series of measured data of biomass components, seed weight, LAI, and soil water content were also visually compared with the predicted curves to further assess the accuracy of the simulations. The values of RMSE, RE (%), and *d* were computed using equations 5, 6, and 7:

$$\text{RMSE} = \left[N^{-1} \sum_{i=1}^{n} (P_i - O_i)^2 \right]^{0.5} \tag{5}$$

$$\text{RE}\,(\%) = \left(\frac{P_i - O_i}{O_i} \right) \times 100 \tag{6}$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} \left(|P_i'| + |O_i'| \right)^2} \right], 0 \le d \le 1 \tag{7}$$

where N is the number of observed values, P_i and O_i are the predicted and observed values for the *i*th data pair, $P_i' = P_i - \overline{O}$ and $O_i' = O_i - \overline{O}$, and $\overline{O}$ is the mean of the observed values. When evaluating the performance of the simulations, the closer the RMSE is to 0, the better the agreement between simulated and observed values. The degree of fit in the relationship between observed and simulated biomass was evaluated through the relative error (RE). The departure from 0 can be used as a measure of under- or overprediction of the observed values by the model. A value of 1 for the index of agreement (*d*) indicates a good agreement between the simulated and observed data.

RESULTS AND DISCUSSION

MODEL CALIBRATION

Soil Water Holding Characteristics

Initial soil properties calculated with the SBuild program of DSSAT Version 4.0 (table 1) were modified based on the observed soil moisture values of the control treatment in order to improve the simulated soil water content. For the top soil horizons, the final values for the soil properties LL and DUL were higher than the initial values. In contrast, the final soil properties for the bottom horizons did not exhibit much difference with respect to the initial values.

Table 1. Description of the Tifton soil profile for the experiment conducted at the Gibbs Farm, Tifton, Georgia.

Depth (cm)	Horizon	Clay (%)	Silt (%)	Permanent Wilting Point (LL, cm^3 cm^{-3})		Field Capacity (DUL, cm^3 cm^{-3})		Saturated Water Content (SAT, cm^3 cm^{-3})	Bulk Density (g cm^{-3})	Organic Carbon (%)
				Initial[a]	Final[b]	Initial[a]	Final[b]			
0-30	Apc	4.2	10.9	0.051	0.072	0.107	0.125	0.317	1.76	0.74
30-51	Btc1	18.6	11.9	0.092	0.095	0.150	0.160	0.259	1.76	1.08
51-76	Btc2	20.9	12.6	0.102	0.098	0.159	0.175	0.280	1.57	0.34
76-104	Btv1	32.6	13.9	0.183	0.183	0.261	0.261	0.362	1.77	0.19
104-135	Btv2	28.8	15.6	0.156	0.156	0.231	0.231	0.342	1.68	0.25
135-183	Bt	32.5	15.6	0.176	0.176	0.254	0.254	0.353	1.73	0.04
183-216	BC	36.5	15.4	0.200	0.200	0.283	0.283	0.365	1.55	0.23

[a] Adjusted volumetric water content (cm^3 cm^{-3}) at the permanent wilting point (LL) and field capacity (DUL) using calculated volumetric soil water content from soil water tension values measured in the field.

[b] Volumetric water content estimated by the DSSAT V 4.0 software.

Table 2. Prediction accuracy of simulated volumetric soil water content for the control treatment combinations of drought stress and fumigation evaluated at the 15-30 cm, 30-45 cm, and 45-60 cm soil depths.

Depth (cm)	Treatment[a]	RMSE (cm^3 cm^{-3})[b]	d[c]	N[d]
15-30	1+	0.024	0.65	109
	1-	0.028	0.70	118
30-45	1+	0.016	0.85	120
	1-	0.034	0.61	110
45-60	1+	0.029	0.72	121
	1-	0.047	0.62	122

[a] 1+ = low drought stress, fumigated.
1- = low drought stress, non-fumigated.

[b] Root mean square error, average over dates.

[c] Index of agreement.

[d] Number of observations.

Soil Water Dynamics

For the control treatment, the simulated volumetric soil water content values at the three soil depths (15-30 cm, 30-45 cm, and 45-60 cm) that were evaluated were close to the observed values, resulting in low values for RMSE (0.016 to 0.047 cm^3 cm^{-3}) and d (0.61 to 0.85) (table 2, fig. 1). The good agreement was exemplified for the top 45 cm, where the increases in simulated changes in volumetric soil water content occurred at rainfall events followed by a decrease in simulated soil water content due to soil drying (fig. 1). The dynamic changes of soil moisture due to the high frequency of irrigation received by this treatment and/or low impact of RKN population on the root system resulted in a more active root system (fig. 1).

Cultivar Coefficients

The values for most of the vegetative and reproductive cultivar coefficients were higher than those from the other commercial cotton cultivars that are part of the DSSAT database, suggesting that the cultivar that was grown in this experiment required more days to the beginning of the reproductive phase (table 3). The difference between observed and simulated values for the flowering and physiological maturity dates of the control treatment was two days. Using the calibrated coefficients improved the total biomass and boll weight predictions by 14.3% and 6.1%, respectively, when compared to the original default values.

Simulated maximum LAI and total biomass were improved by adjusting the soil fertility factor (from 1.0 to 0.82) and increasing the specific leaf area (SLAVR). Decreasing the soil fertility factor reduced the growth rate through modification of the daily canopy photosynthetic rate. The d values for LAI and total biomass of the control treatment were 0.94 and 0.64, respectively.

Finally, the onset of boll formation, photothermal days for seed filling, and final boll load were increased to match boll initiation and weight as well as rate of bolls accumulation. The d values for boll and seed cotton weight in the control treatment were 0.79 and 0.68, respectively.

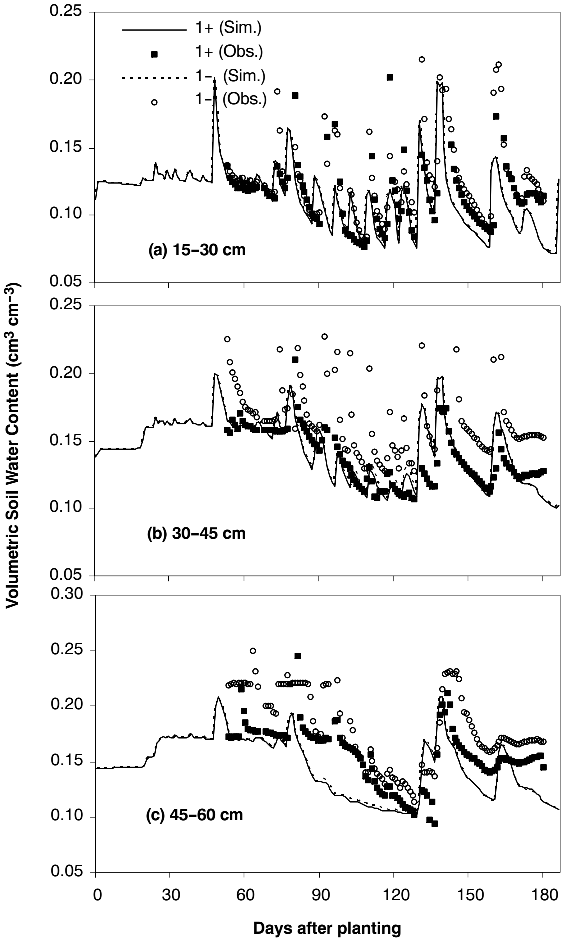

Figure 1. Simulated and observed volumetric soil water content at the 0-60 cm soil depth for the low (1) drought stress treatment, fumigated (+) and non-fumigated (-).

Table 3. Cultivar coefficients of cultivar DP 458 B/RR for the CROPGRO model, before and after calibration.

Cultivar Coefficient	Abbreviation	Calibrated Value	Default Value
Photothermal days from emergence to flower appearance	EM-FL	45	38
Photothermal days from beginning flower to beginning boll	FL-SH	13	12
Photothermal days from beginning flower to beginning seed	FL-SD	22	15
Photothermal days from beginning seed to maturity	SD-PM	50	42
Maximum leaf photosynthesis rate (micromol (CO_2 m^{-2} s^{-1})	LFMAX	1.1	1.1
Specific leaf area (cm^2 g^{-1})	SLAVR	238	170
Maximum size of full leaf (cm^2)	SIZLF	300	300
Maximum fraction of daily growth partitioned to seed + shell	XFRT	0.78	0.85
Maximum weight per seed (g)	WTPSD	0.300	0.18
Photothermal days for seed filling per individual seed	SFDUR	35	30
Average seed numbers per boll (no. $boll^{-1}$)	SDPDV	28	27
Photothermal days to reach final boll load	PODUR	9	8

Table 4. Average RKN population (second-stage juveniles per 150,000 cm^3 soil) measured at different days after planting for the six fumigated and non-fumigated and drought stress treatments.

	2007[b]				2001[c]		
Treatment[a]	18 DAP[d]	66 DAP	118 DAP	175 DAP	51 DAP	71 DAP	197 DAP
1+	5000	10000	100000	265000	30000	7000	101667
1-	23333	36667	210000	211667	76667	304000	160000
2+	0	16667	111667	221667	20000	16667	70000
2-	28333	38333	345000	288333	61667	200333	181667
3+	5000	6667	191667	213333	15000	15000	176667
3-	28333	0	361667	205000	60000	250333	435000

[a] 1+ = low drought stress, fumigated; 1- = low drought stress, non-fumigated; 2+ = medium drought stress, fumigated; 2- = medium drought stress, non-fumigated; 3+ = severe drought stress, fumigated; and 3- = severe drought stress, non-fumigated.

[b] RKN population density data for model calibration.

[c] RKN population density data for model evaluation.

[d] Days after planting.

MODEL ADAPTATION: HYPOTHESIS 1: RKN AS SINK FOR SOLUBLE ASSIMILATES

Following calibration of the soil parameters and cultivar coefficients, the model was modified in order to be able to simulate the potential impact of RKN, as described earlier. A final assimilate consumption rate value of 0.0012 g CH_2O RKN-$J2^{-1}$ d^{-1} was obtained after minimizing the error between simulated and observed biomass and yield components (boll and seed cotton weight) and the growth analysis data for the low drought stress, non-fumigated treatment (1-).

The differences in RKN population levels between treatments influenced the amount of assimilate that was removed from the shoot, although a constant rate of assimilate consumption was used (table 4, fig. 2). In this study, the highest amount of assimilate was removed from 90 to 120 DAP, corresponding to the stages of flowering and boll filling. Therefore, the implementation of this strategy to mimic RKN damage should account for reductions in yield and yield components.

Total Biomass

The model simulations showed that cotton biomass decreased severely as the RKN population and the level of drought stress increased (fig. 3). There was overprediction for biomass for the non-fumigated treatments, with a relative error of prediction (RE) of 24.0%, 16.7%, and 19.6% for the 1-, 2-, and 3- treatments, respectively (table 5). The overprediction of biomass could be associated with high simulated values of stem-petiole biomass throughout the growing season (data not shown). The growth analysis data for total biomass for the low drought stress treatment were fairly well simulated, with *d* values of 0.64 and 0.75 for the 1+ and 1- treatments, respectively (table 5, fig. 3a). The percentage reduction in biomass between the fumigated and non-fumigated treatments increased with the level of stress, being 6%, 18%, and 17% less for the low, medium, and severe drought stress levels, respectively. This reduction could be associated with the higher amount of assimilate removed by RKN on non-fumigated plots (fig. 2).

Boll Weight

The changes in boll weight accumulation throughout the season and the final boll weight at harvest were fairly well predicted by the CSM-CROPGRO-Cotton model (table 6, figs. 4a through 4c). The dynamics of boll weight accumulation were best predicted for the non-fumigated treatments, with RMSE values of 1356, 1749, and 1640 kg ha^{-1} for the 1-, 2-, and 3- treatments, respectively (table 6). The RE values for the 2- and 3- treatments (-2.8% and -3.9%) were lower than the RE values for the 2+ and 3+ treatments (7.2% and -0.9%). For the 3+ treatment, the final boll weight was underpredicted by 33 kg ha^{-1}, which was the most accurate simulation of all treatments. The highest differences between simulated and observed final boll weight (576 kg ha^{-1}) was observed for the 1- treatment.

The high RKN population of the 2- and 3- treatments compared to the 1- treatment increased the removal of assimilates, especially during the flowering and boll filling stage, suggesting a high contribution of the RKN population to the reduction in boll weight (fig. 2). Boll weight was reduced 33% (1707 kg ha^{-1}) for the 2- treatment compared to the 1- treatment, and 39% (2020 kg ha^{-1}) for the 3- treatment compared to the 1- treatment. Additionally, the percentage reduction of boll weight between the fumigated and non-fumigated treatments increased as the level of stress

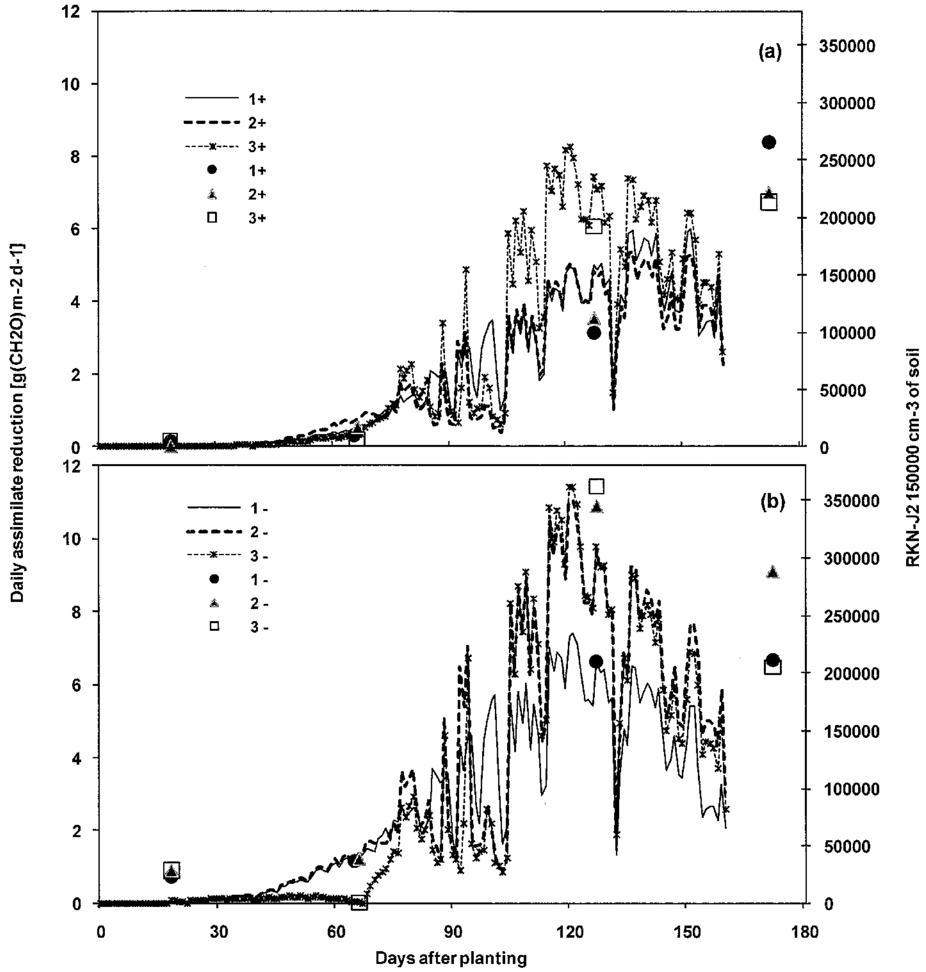

Figure 2. Differences in RKN-J2 population density (dots) and daily assimilate removal (lines) as calculated by the CSM-CROPGRO-Cotton model for low (1), medium (2), and high (3) drought stress: (a) fumigated (+), and (b) non-fumigated (-).

increased: 8.4%, 24%, and 19% for the low, medium, and severe drought stress, respectively. Because the irrigation for the medium and severe drought stress treatments was reduced in July, which corresponded to the squaring and flowering period, the reductions in boll weight could be associated with square and flower loss.

The simulations showed a higher impact of severe drought stress for the fumigated treatments compared to the low drought stress (32% reduction in boll weight). However, this reduction in boll biomass was the result of the interaction between severe drought stress and RKN population.

Seed Cotton Weight

The dynamics of seed cotton were very well simulated, with values within one standard deviation of the measured mean for all treatments (figs. 4d through 4f). The RMSE for seed cotton at harvest for the fumigated treatments was 691, 875, and 745 kg ha^{-1} for the low, medium, and severe drought stress treatments, respectively. The same drought stress treatments under non-fumigation had RMSE values of 930, 1119, and 989 kg ha^{-1}, respectively (table 6).

The most accurate predictions were observed for the 1+ treatment, followed by the 1–, and 2+ treatments, with RE values of 0.1, 1.0, and 2.3, respectively. Seed cotton for the severe drought stress treatment exhibited the highest RE values, with -5.8% and -8.2% for the fumigated and non-fumigated treatments, respectively. This could be explained by the high variation of seed cotton between replications, as evidenced by standard deviation values of 712 kg ha^{-1} for the 3+ treatment and 889 kg ha^{-1} for the 3– treatment.

Table 5. Simulated and observed total biomass at harvest for the six treatments of the 2007 experiment conducted at the Gibbs Farm, Tifton, Georgia.

	Total Biomass (kg ha^{-1})				
Treatment[a]	Simulated	Observed	RMSE[b]	RE (%)[c]	*d*[d]
1+	9456	8013	3556	18.0	0.64
1-	8877	7159	2233	24.0	0.75
2+	7798	6805	2941	14.6	0.63
2-	6412	5493	2735	16.7	0.57
3+	7076	6709	3106	5.5	0.58
3-	5891	4925	2420	19.6	0.54

[a] 1+ = low drought stress, fumigated.
1- = low drought stress, non-fumigated.
2+ = medium drought stress, fumigated.
2- = medium drought stress, non-fumigated.
3+ = severe drought stress, fumigated.
3- = severe drought stress, non-fumigated.
[b] Root mean square error, average over dates.
[c] Relative error (percentage).
[d] Index of agreement.

The model simulation indicated that seed cotton was highly impacted by the RKN population as well as drought

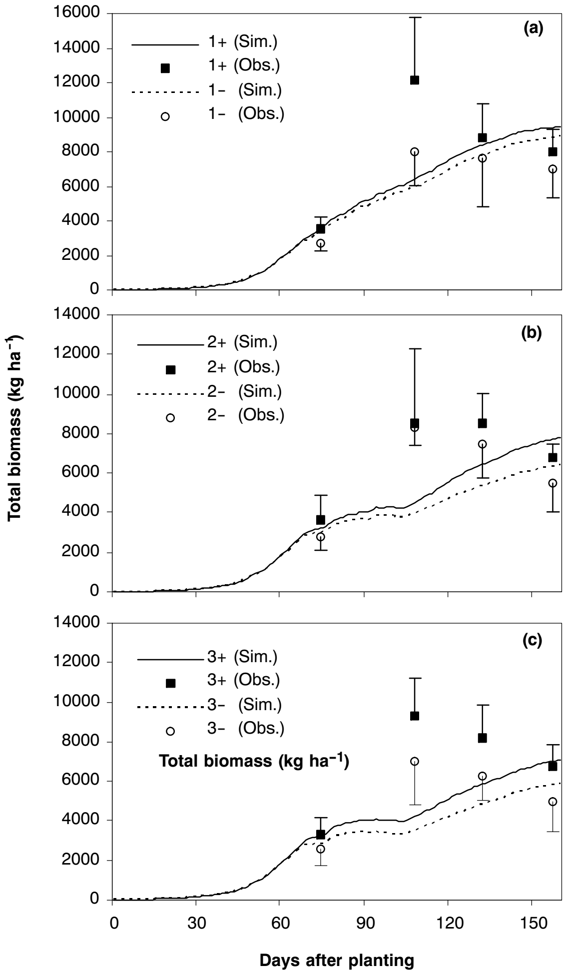

Figure 3. Simulated and observed total biomass corresponding to low (1), medium (2), and severe (3) drought stress treatments, fumigated (+) and non-fumigated (-). Error bars represent one standard deviation, and points represent the mean of the measured data.

stress. Final seed cotton weight decreased by an average of 1330 kg ha^{-1} when the level of drought and the amount of removed assimilate increased from low to severe for the non-fumigated plots (table 6, figs. 2 through 4). A similar trend was observed for the measured seed cotton weight at harvest, where the reduction in weight for severe drought stress compared to low drought stress for the fumigated plots was 1096 kg ha^{-1}. For the fumigated treatments, although there were no big differences in assimilate consumption, the simulations showed a reduction of 30% for seed cotton for the severe drought stress treatments (3+) compared to the low drought stress treatments (1+).

When modeling, it is very important to be able to predict relative differences in management practices, which in this case correspond to fumigation and non-fumigation. An increase in assimilate consumption by RKN-J2 for the non-fumigated treatments caused a reduction in the simulated seed cotton with an increase from low to severe drought stress, e.g., 10%, 24%, and 20%, respectively. A similar trend was observed when the percentage reduction in observed seed cotton was calculated for the same treatments, e.g., 11%, 14%, and 18%. These results suggest that the modeling strategies implemented to account for RKN parasitism could be used to asses potential yield reduction due RKN population as well as a combined negative effect of drought stress and high RKN population.

MODEL ADAPTATION: HYPOTHESIS 2: RKN INDUCES A REDUCTION IN ROOT LENGTH PER UNIT ROOT MASS AND ROOT LENGTH DENSITY

When the hypothesis of RKN as sink of soluble assimilate was tested for the three non-fumigated (-) treatments, the simulated LAI was still overpredicted, which was more evident under severe drought stress (table 7). This showed the need for using an additional strategy for the RKN-J2 as a sink of soluble assimilates to account for the early reduction in LAI, perhaps because RKN-J2 were extracted from the soil after root damage had been caused. The second hypothesis was implemented by setting the RFAC1, i.e., the root length to root weight ratio, to 17000 cm root g^{-1} for the fumigated treatments and reducing it to 14000 cm root g^{-1} for the 1- and 2- treatments and to 8800 cm root g^{-1} for the 3- treatment. These final values were obtained after minimizing the error between simulated and observed LAI and improving the overall prediction of LAI throughout the growing season (table 7).

Leaf Area Index

The implementation of this hypothesis appeared to predict the time series of LAI fairly well for all the treatments compared to hypothesis 1 (table 8, fig. 5). The most accurate simulations of LAI occurred for the 1+, 2-, and 3- treatments, with the lowest RMSE (0.69, 0.70, and 0.63 m^2 m^{-2}) and high *d* values (0.94, 0.86, and 0.86) (table 8). The highest RMSE observed for the 1- treatment (0.99 m^2 m^{-2})

Table 6. Simulated and observed bolls weight and seed cotton weight at maturity for the six treatments of the 2007 experiment conducted at the Gibbs Farm, Tifton, Georgia.

	Boll Yield (kg ha^{-1})					Seed Plus Lint Yield (kg ha^{-1})				
Treatment[a]	Simulated	Observed	RMSE[b]	RE (%)[c]	*d*[d]	Simulated	Observed	RMSE[b]	RE (%)[c]	*d*[d]
1+	5590	5347	2099	4.5	0.79	3974	3972	691	0.1	0.68
1-	5117	4541	1356	12.7	0.86	3571	3536	930	1.0	0.63
2+	4471	4170	1801	7.2	0.78	3253	3181	875	2.3	0.52
2-	3410	3508	1749	-2.8	0.70	2462	2738	1119	-10.1	0.48
3+	3823	3856	2337	-0.9	0.63	2791	2964	745	-5.8	0.68
3-	3097	3223	1640	-3.9	0.66	2241	2440	989	-8.2	0.53

[a] 1+ = low drought stress, fumigated; 1- = low drought stress, non-fumigated; 2+ = medium drought stress, fumigated; 2- = medium drought stress, non-fumigated; 3+ = severe drought stress, fumigated; and 3- = severe drought stress, non-fumigated.

[b] Root mean square error, average over dates.

[c] Relative error (percentage).

[d] Index of agreement.

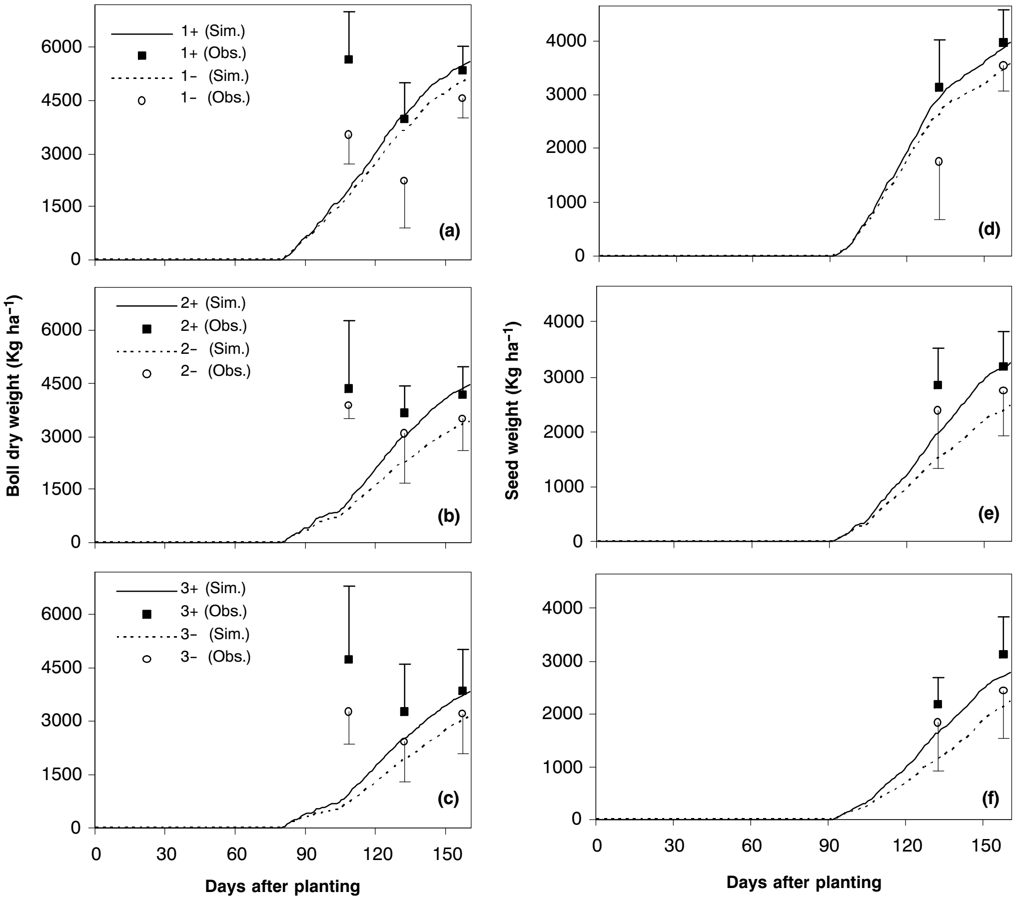

Figure 4. Simulated and observed boll dry weight and seed cotton weight corresponding to low (1), medium (2), and severe (3) drought stress treatments, fumigated (+) and non-fumigated (-). Error bars represent one standard deviation, and points represent the mean of measured data.

Table 7. Prediction accuracy of simulated maximum leaf area index (LAI) before and after modeling RKN damage. Values correspond to the non-fumigated treatment (-) with low (1), medium (2), and severe (3) drought stress.

				Prediction Assessment			
	LAI (m^2 m^{-2})[b]			RMSE[c]		d[d]	
Treatment[a]	Measured	Initial	Final	Initial	Final	Initial	Final
1-	4.57	4.76	4.57	1.05	0.99	0.84	0.85
2-	3.67	3.83	3.67	0.71	0.70	0.86	0.86
3-	3.39	4.01	3.41	0.69	0.63	0.87	0.86

[a] 1- = low drought stress, non-fumigated; 2- = medium drought stress, non-fumigated; and 3- = severe drought stress, non-fumigated.
[b] Values of maximum LAI: measured in the field, initially simulated using the 1st hypothesis, and finally simulated using the 2nd hypothesis.
[c] Root mean square error, average over dates.
[d] Index of agreement.

showed the inability of the model to accurately simulate leaf senesce at the end of the growing season for this particular condition (fig. 5a). For the fumigated (+) treatments, particularly the 2+ and 3+ treatments, maximum LAI (occurring around 90 DAP) was underestimated, with an RMSE of 0.78 and 0.77, respectively, while for the 2- and 3- treatments (non-fumigated), maximum LAI was very well simulated. The simulations showed that the difference in maximum LAI between fumigated and non-fumigated cotton plants increased as the level of drought stress increased. The percentage reduction in maximum LAI due to an increase in RKN population for the non-fumigated treatments compared to the fumigated treatments was 7%, 8%, and 15% for the low, medium, and severe drought stress levels, respectively (table 8).

MODEL EVALUATION

The values for assimilate consumption rate (ASMDOT) and root length per unit root weight (RFAC1) that were obtained after model adaptation were used for model evaluation with data that were collected from an experiment that was conducted in 2001. Both the 2001 and 2007 experiments were conducted at the same site and were part of a long-term crop rotation experiment. The RKN-J2 population was collected three times during the growing season and was used as input for the model to simulate the impact of RKN on cotton yield (table 4). Because seed cotton weight was the only variable collected in 2001, it was not possible to determine the goodness of fit for each hypothesis.

Based on the model simulations, it was evident that there was a reduction in seed cotton weight as RKN population

Table 8. Simulated and observed maximum leaf area index (LAI) for the six treatments of the 2007 experiment conducted at the Gibbs Farm, Tifton, Georgia.

	LAI (m^2 m^{-2})				
Treatment[a]	Simulated	Observed	RMSE[b]	RE (%)[c]	*d*[d]
1+	4.92	5.08	0.69	-3.1	0.94
1-	4.57	4.57	0.99	0.0	0.85
2+	3.97	4.62	0.78	-14.1	0.85
2-	3.67	3.67	0.70	0.0	0.86
3+	4.01	4.97	0.77	-19.3	0.87
3-	3.41	3.39	0.63	0.6	0.86

[a] 1+ = low drought stress, fumigated.
1- = low drought stress, non-fumigated.
2+ = medium drought stress, fumigated.
2- = medium drought stress, non-fumigated.
3+ = severe drought stress, fumigated.
3- = severe drought stress, non-fumigated.

[b] Root mean square error, average over dates.

[c] Relative error (percentage).

[d] Index of agreement.

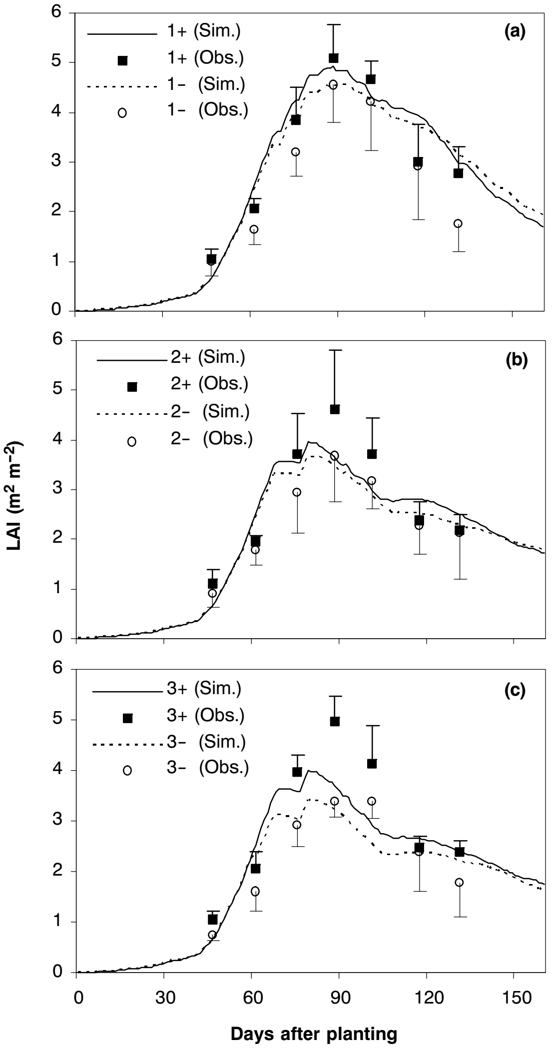

Figure 5. Simulated and observed leaf area index (LAI) corresponding to low (1), medium (2), and severe (3) drought stress treatments, fumigated (+) and non-fumigated (-). Error bars represent one standard deviation, and points represent the mean of measured data.

Table 9. Simulated and observed seed cotton weight at harvest for the six treatments of the 2001 experiment conducted at the Gibbs Farm, Tifton, Georgia.

	Seed Cotton Weight (kg ha^{-1})[b]			
Treatment[a]	Simulated	Observed	RMSE[c]	RE (%)[d]
1+	4147	3069	1171	35.1
1-	2757	2895	392	-4.8
2+	3432	3064	469	12.0
2-	2634	2785	437	-5.4
3+	2706	2939	313	-7.9
3-	1632	2160	1049	-24.4

[a] 1+ = low drought stress, fumigated.
1- = low drought stress, non-fumigated.
2+ = medium drought stress, fumigated.
2- = medium drought stress, non-fumigated.
3+ = severe drought stress, fumigated.
3- = severe drought stress, non-fumigated.

[b] Seed cotton weight is equivalent to seed plus lint weight.

[c] Root mean square error.

[d] Relative error (percentage).

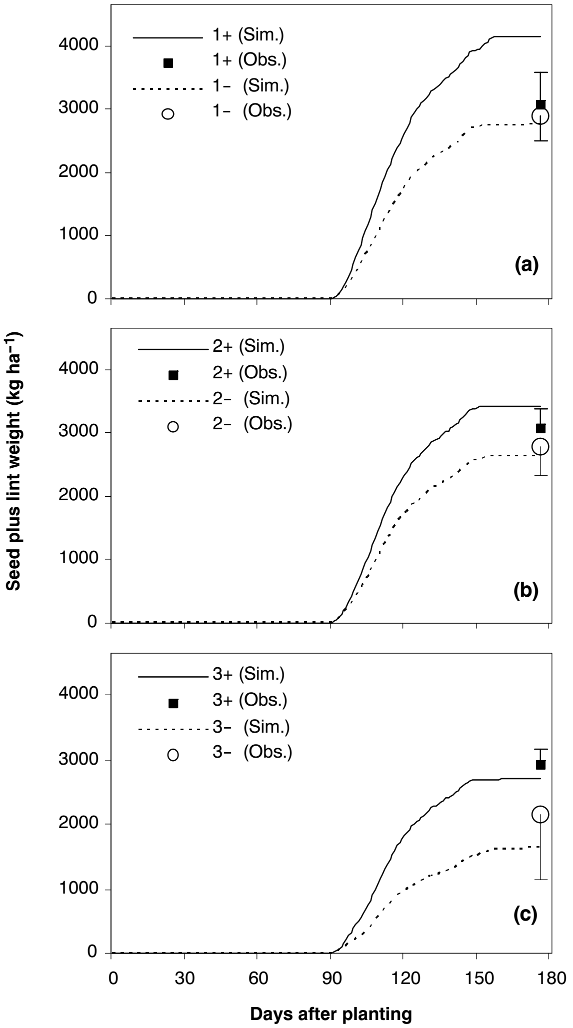

Figure 6. Simulated and observed seed cotton weight for the 2001 experiment for low (1), medium (2), and severe (3) drought stress treatments, fumigated (+) and non-fumigated (-). Error bars represent one standard deviation, and points represent the mean of the observed data.

increased on the non-fumigated plots, which reaffirmed the results from the model calibration. The reduction in seed cotton weight for non-fumigated plots compared to the fumigated plots were 34%, 23%, and 40% for the low, medium, and severe drought stress treatments, respectively (table 9, fig. 6). For some of the treatment combinations of drought stress and fumigation (1+ and 2+), seed cotton weight was overpredicted, with RE values of 35.1%, and 12%, respectively (table 9). However, the predicted seed cotton weight for the 1- and 2- treatments was the most accurate, with RE values of -4.8% and -5.4%, respectively.

Although the relative error of prediction for the low and medium drought stress with fumigation treatments was high compared to the other treatments, the relative difference between fumigation and non-fumigation calculated from the simulated and observed values for the severe drought stress treatments was the highest for all treatments, with values of 40% and 27%, respectively. The percentage reduction for both the simulated and observed seed cotton weight between the fumigated and non-fumigated treatments increased as drought stress increased. Except for the seed cotton weight of the severe drought stress, non-fumigated treatment, which was underpredicted by 24%, the RMSE and RE of the other non-fumigated treatments was low and was only underpredicted by 5%. These results validate the significance of using the two hypotheses that were tested here to account for RKN damage using the CSM-CROPGRO-Cotton model. They also show that this approach can be used to estimate potential yield loss when cotton fields are at risk for high population of RKN and drought stress.

SUMMARY AND CONCLUSION

The CSM-CROPGRO-Cotton model was modified by coupling the RKN population to the removal of daily assimilates and decreasing the root length per unit mass as strategies to mimic RKN damage. Once the RKN effects were accounted for in the CSM-CROPGRO-Cotton model, the simulated vegetative and reproductive biomass components were close to the observed values for the three drought stress levels and fumigation levels. Changes in LAI and boll weight were very well simulated by the model, especially for the non-fumigated treatments. Model simulations indicated that LAI, total biomass, boll weight, and seed cotton weight decreased with an increase in RKN population for the non-fumigated plots. The impact of RKN was more pronounced under severe drought stress. For both the fumigated and non-fumigated treatments, LAI, biomass weight, and seed cotton weight decreased with increasing drought stress. The model underpredicted maximum LAI for all fumigated treatments. This was more pronounced for the fumigated treatment under medium and severe drought stress. Total biomass values were overpredicted by an average of 17% for all treatments. The simulated seed cotton losses due to the RKN population increased with water stress. The simulations with the 2007 model adaptation data set showed seed cotton losses of 10%, 24%, and 20% for the low, medium, and severe drought stress treatments, respectively. The simulations with the 2001 evaluation data set showed seed cotton losses of 34%, 23%, and 40% for the low, medium, and severe drought stress, respectively.

In conclusion, the CSM-CROPGRO-Cotton model in DSSAT v4.0 was able to simulate growth and yield due to RKN damage and drought stress within ±30% error from the measured values. It also simulated soil water dynamics for the different drought stress levels. The two hypotheses to account for RKN damage were successfully implemented, and LAI, biomass, and cotton seed weight for plots that had a high population of RKN were simulated accurately. The first hypothesis considered RKN as a sink of soluble assimilates and targeted reductions in biomass and yield components (bolls and seed cotton). The second hypothesis accounted for reductions in root length per unit mass due to RKN parasitism and allowed the simulations of LAI under different levels of RKN population. Although it was difficult to individually test each hypothesis because of the high variation of the RKN population between treatments, the results from this study suggest that both strategies should be combined to simulate potential yield losses associated with RKN population.

‘The results presented in this study showed the potential of the CSM-CROPGRO-Cotton model for determining the impact of RKN and drought stress in cotton and understanding the effect of these stressor factors on growth and final yield when changing management strategies. Future research should involve the identification and implementation of other methods to improve the prediction of RKN damage, such as the addition of disease progress functions to better simulate within-season change in RKN populations and its effect on growth and yield. Additionally, there is a need for further evaluation of the model for other weather and soil conditions and management practices in order to establish the levels of risk for high populations of nematode and identify possible pest management strategies.

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