Development and Evaluation of the RZWQM-CROPGRO Hybrid Model for Soybean Production

L. Ma,* G. Hoogenboom, L. R. Ahuja, D. C. Nielsen, and J. C. Ascough II

ABSTRACT

It is common for agricultural system modelers to enhance their models by learning from other models and incorporating the best state-of-the-science into their models. In this study, the CROPGRO plant growth model of Decision Support System for Agrotechnology Transfer (DSSAT v3.5) was linked to the Root Zone Water Quality Model (RZWQM) to provide RZWQM users an option of using CROPGRO. In the hybrid model, RZWQM supplied CROPGRO with daily soil water and N, soil temperature, and potential evapotranspiration (PET), whereas CROPGRO supplied RZWQM with daily water and N uptake and plant growth variables. The RZWQM-CROPGRO hybrid model was then evaluated against the original CROPGRO-soybean model using several data sets from the literature. These data sets represented various drought conditions. Results showed that the RZWQM-CROPGRO hybrid model simulated higher water stress than the original DSSAT-CROPGRO model because of higher PET simulated by RZWQM, especially under semiarid climate conditions. Therefore, it was necessary to make some adjustments in the hybrid model under dry and windy conditions, e.g., using a different lower limit of plant available water as DSSAT. The hybrid model with a more detailed soil water balance calculation only affected soil water prediction at the top 60-cm soil profile where soil water was more dynamic. This study demonstrated a successful linkage between RZWQM and CROPGRO, and the RZWQM-CROPGRO hybrid model provides users with a tool to conduct detailed simulation of crop production in addition to addressing water quality concerns. This study also demonstrated that, when building models from various sources, compatibility of the interacting modules should be ensured.

Agricultural system models have untapped potential to help agricultural research and technology transfer in the 21st century (Ahuja et al., 2002a). Examples of these models are GLYCIM (Timlin et al., 2002), GOSSYM (Reddy et al., 2002), CERES and CROPGRO (Tsuji et al., 2002), APSIM (McCown et al., 2002), and RZWQM and GPFARM (Ahuja et al., 2002b). In recent years, agricultural system models have shifted from being mainly research oriented to tools for guiding resource management and policy-making. The linkage of these models to geographic information systems (GIS) and decision support systems has added new dimensions to model applications (Hartkamp et al., 1999; Ahuja et al., 2002a). The more recent development of Window-based user interfaces makes model application much easier (Georgiev and Hoogenboom, 1999; Rojas et al., 2000).

Although models are a synthesis and quantification of governing processes (e.g., biological, physical, and chemical) in an agricultural system based on current theoretical and experimental knowledge, process details of the models vary widely depending on the objectives and timeframe of the model developers (Ma and Shaffer, 2001; McGechan and Wu, 2001). Many agricultural system models use components from other existing models to save development time. For example, the original soybean [*Glycine max* (L.) Merr.] crop growth model, SOYGRO, developed at the University of Florida, used the soil water and N balance component from the CERES-maize model (Hoogenboom et al., 1992) and was released as part of DSSAT v3.5 (Tsuji et al., 1994; Ritchie, 1998; Boote et al., 1998; Hoogenboom et al., 1999). Recently, the soil organic C and N module from the CENTURY model was linked to the DSSAT package (Gijsman et al., 2002; Jones et al., 2003). Ma et al. (2005) demonstrated a successful linkage between RZWQM and the CERES-maize crop growth model of DSSAT 3.5.

In this study, we further developed a linkage between the USDA-ARS RZWQM (Ahuja et al., 2000) and CROPGRO model of DSSAT v3.5 (Hoogenboom et al., 1999; Tsuji et al., 1994) to capture years of plant growth modeling experience of the DSSAT developers in RZWQM. Although the generic plant growth module in RZWQM is adequate for simulating corn (*Zea mays* L.), soybean, and winter wheat (*Triticum aestivum* L.) under certain conditions (Ma et al., 2002, 2003; Nielsen et al., 2002; Saseendran et al., 2004), RZWQM cannot simulate yield components and is weak in phenology simulation. Thus, it is of great interest for RZWQM users to have an option to use the CROPGRO plant growth model. The objectives of this study were to develop and evaluate the RZWQM-CROPGRO hybrid model using well-documented data sets and to identify areas and conditions where a hybrid model may not work and special attention should be paid. Our purpose was to demonstrate the potential in linking the "strong" modeling components of two completely different modeling systems to improve the applicability of both models.

THE RZWQM-CROPGRO HYBRID MODEL

In the RZWQM-CROPGRO hybrid model, we kept the integrity of CROPGRO as much as possible so that

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Abbreviations: AET, actual evapotranspiration; DSSAT, Decision Support System for Agrotechnology Transfer; DUL, drained upper limit; LAI, leaf area index; LL, soil lower limit of plant available water; LL15, 1500 kPa soil water content; PET, potential evapotranspiration; RMSE, root mean square error; RZWQM, Root Zone Water Quality Model; SRGF, root growth distribution factor.

all crop-related parameters would be preserved. In particular, RZWQM provided CROPGRO only with daily soil water and N status, daily soil temperature, and PET, in addition to daily weather input and soil physical properties. The reason for using the RZWQM PET module was to preserve the effects of partial canopy and crop residue on PET and the wind effects on PET using the Shuttleworth–Wallace method (Shuttleworth and Wallace, 1985), rather than the Priestley–Taylor approach (Priestley and Taylor, 1972) used in the DSSAT models. The CROPGRO module supplied RZWQM with daily water and N uptake, daily N fixation, and plant growth variables [e.g., root distribution, leaf area index (LAI), plant height, and growth stage]. After harvest, nonharvestable aboveground biomass and root biomass were returned to the soil in RZWQM as crop residues. Water and N stress factors for plant growth were calculated by CROPGRO. Basically, CROPGRO substituted the original generic plant growth module in RZWQM (Hanson, 2000). The RZWQM-CROPGRO hybrid model operates in the RZWQM Windows user interface (Rojas et al., 2000), and users can review simulation results in both RZWQM and DSSAT data and file formats. The results can be plotted and compared with experimental results using the DSSAT graphics software as well.

A FORTRAN subroutine facilitated data and information transfer between RZWQM and CROPGRO. Since RZWQM and DSSAT used different numerical grids for the soil profile, the subroutine converted soil water, soil N, and soil temperature from one grid to another on a daily basis. We also assumed that the drained upper limit (DUL) was equivalent to the soil water content at 33 kPa and the lower limit of plant available water (LL) was equivalent to the soil water content at 1500 kPa (LL15) (Ritchie, 1998). After the hybrid was developed, the RZWQM-CROPGO hybrid model was verified through numerical testing for correct transferring of variables between the two models before it was evaluated against experimental data.

Crop cultivar parameters can be managed using a Windows interface (Fig. 1) in RZWQM-CROPGRO, and users can select a cultivar from the DSSAT genotype database or create a new cultivar. Simulation controls and the root growth distribution factor (SRGF) are also facilitated by a Windows interface (Fig. 2). These Windows interfaces are part of the crop management options, and users can activate the CROPGRO plant growth module by simply selecting a cultivar from the DSSAT genotype database in Fig. 1 and then modifying its parameters if necessary. Output files for the hybrid model have the same formats as in the original DSSAT model.

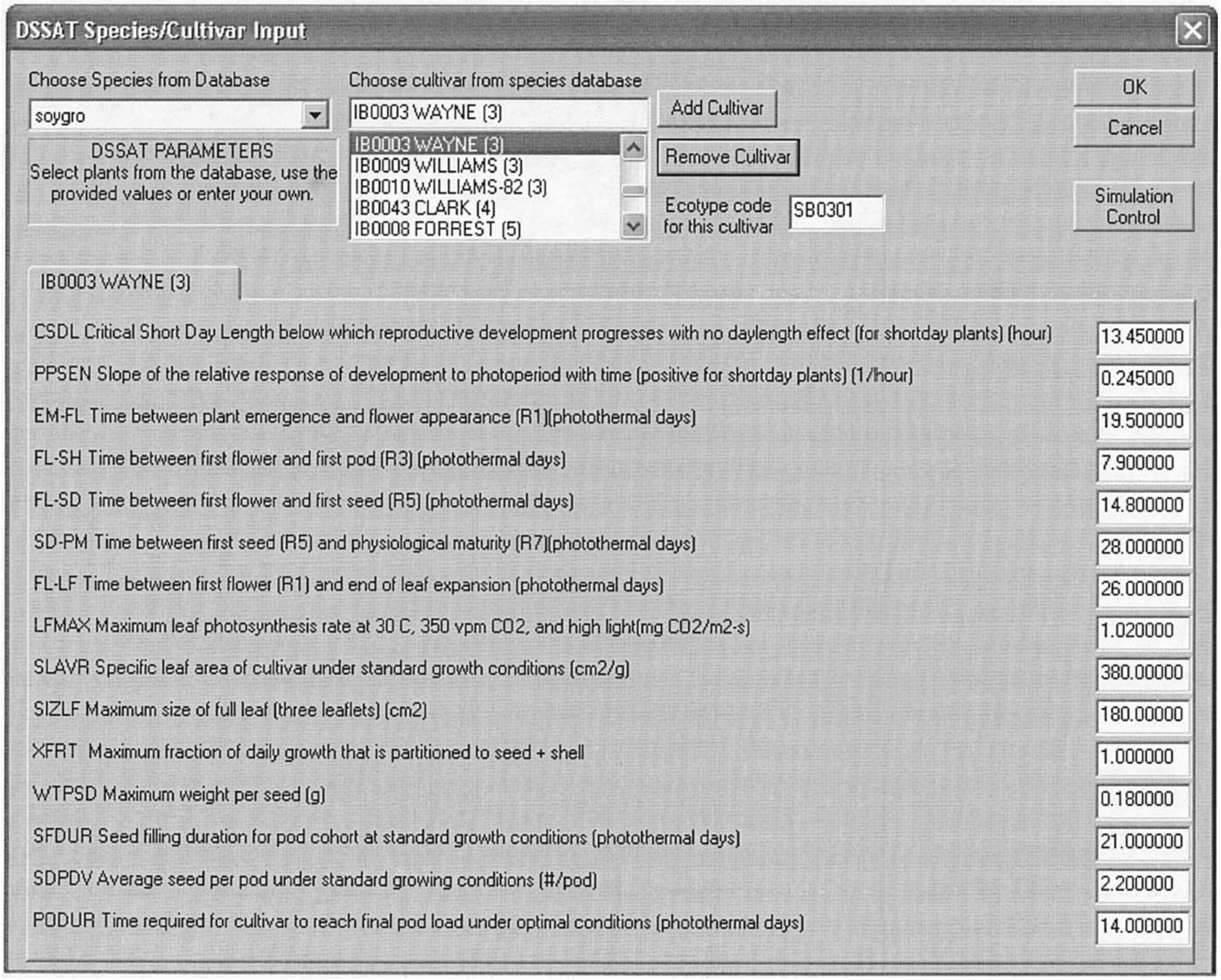
MATERIALS AND METHODS

Three years of data (1978, 1979, and 1981) from Gainesville, FL and 2 yr of data (1985 and 1986) from Akron, CO were chosen to evaluate the RZWQM-CROPGRO hybrid model in comparison with results from the original DSSAT-CROPGRO model. These data sets were simulated previously with the DSSAT-CROPGRO model and had multiple water treatment levels (Ma et al., 2002; Nielsen et al., 2002; Boote et al., 1998; Calmon et al., 1999). The Colorado study represents a semiarid weather condition, and the Florida study represents a humid weather condition.

The experiments selected from DSSAT were UFGA7801, UFGA7901, and UFGA8101. Detailed information is available at Boote et al. (1998), Hoogenboom et al. (1992), and Calmon et al. (1999) as well as the ICASA Data Exchange (IDE) at www.icasa.net (verified 21 Apr. 2005) (Tsuji et al., 1994; Hoogenboom et al., 1999; Bostick et al., 2004). The UFGA7801, UFGA7901, and UFGA8101 data sets were from studies conducted at the University of Florida in Gainesville, FL in 1978, 1979, and 1981, respectively. The soil was a Millhopper fine sand (loamy, siliceous, hyperthermic Grossarenic Paleudults). For UFGA7801, the cultivar Bragg (Maturity Group 7) was planted on 15 June 1978 to a density of 29.9 plants m^{-2}. Two treatments were designed: one rainfed without irrigation and the other with 21 irrigations for a total of 155 mm of water from 16 June 1978 to 21 Oct. 1978. The same soybean variety was planted on 19 June 1979 to a density of 47.0 plants m^{-2}. The two irrigation treatments were full irrigation with 85 mm of irrigation from 13 July 1979 to 14 Oct. 1979 and rainfed (no irrigation). For the third experiment (UFGA8101), the variety Cobb (Maturity Group 8) was planted on 26 June 1981 at a density of 35.9 plants m^{-2}. The three irrigation treatments were 237 mm (Full), 155 mm with vegetative stress, and 199 mm with reproductive stress from 30 June 1981 to 23 Oct. 1981. Measurements included vegetative and reproductive development (anthesis, first pod, first seed, and physiological maturity) and growth analysis at regular time intervals to determine LAI, leaf biomass, stem biomass, seed weight, pot weight, and seed number. At harvest, the yield and yield components were measured.

The Akron, CO study was designed to investigate the effect of irrigation on soybean production (Ma et al., 2002; Nielsen et al., 2002). The soil was a Rago silt loam (fine smectitic, mesic Pachic Argiustoll). Soil texture and bulk density were measured and reported in Nielsen et al. (2002). Details regarding the irrigation system can be found in Nielsen (1990, 1997). A line-source gradient irrigation system was used with full irrigation next to the irrigation line and linearly declining water applications with distance away from the line source. Four irrigation treatments were identified from the plots based on the distances from the line source. The cultivar Pioneer Brand 9291 (Late Group II) was planted on 23 May 1985 and 20 May 1986, with a density of 37.5 and 26.2 plants m^{-2}, respectively. Irrigation started on 22 June 1985 and ended on 28 Aug. 1985 (five irrigation events) with total irrigation amounts of 2.8, 33.8, 88.6, and 129.2 mm for Treatments 1, 2, 3, and 4, respectively (Ma et al., 2002). Nine irrigation events were scheduled in 1986 from 25 June to 25 August, with total irrigation amounts of 15.5, 72.2, 171.1, and 249.8 mm for Treatments 1, 2, 3, and 4, respectively (Ma et al., 2002). Soil water content was measured with a neutron probe during the growing season to a depth of 1.80 m at 0.30-m increments from 10 July to 25 September in 1985 and from 20 June to 26 September in 1986. At harvest, grain yields were recorded. In 1985, plant biomass and LAI were measured four times during the growing season from 25 June to 14 August.

To compare the RZWQM-CROPGRO hybrid model with DSSAT-CROPGRO, both models were run with same soil properties. Since RZWQM required rainfall duration, a 2-h duration was assumed whenever rainfall duration was not given. Also, a breeze of 100 km/d was assumed whenever wind speed was missing for the Shuttleworth–Wallace PET calculation (Farahani and DeCoursey, 2000). Comparison of the DSSAT-CROPGRO and RZWQM-CROPGRO models was made based on soil water balance, soybean biomass, and yield components. A paired *t* test was used to calculate which model provided simulation results closer to experimental val-



Choose Species from Database: soygro

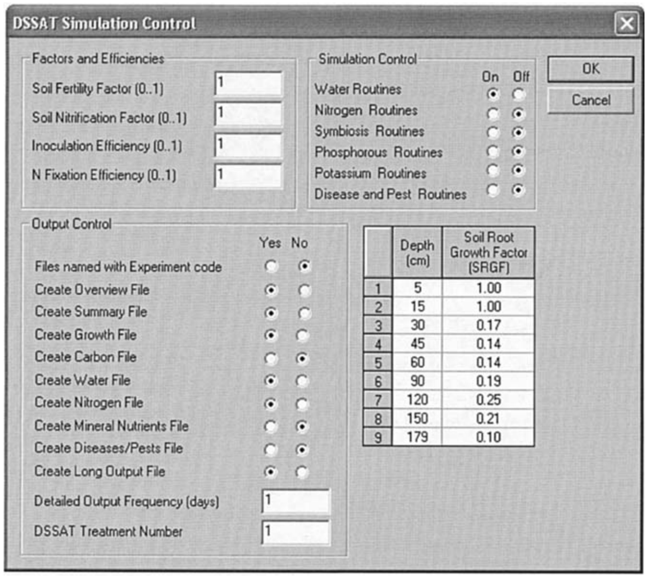
Choose cultivar from species database: IB0003 WAYNE (3)

Ecotype code for this cultivar: SB0301

IB0003 WAYNE (3)

CSDL Critical Short Day Length below which reproductive development progresses with no daylength effect (for shortday plants) (hour)	13.450000
PPSEN Slope of the relative response of development to photoperiod with time (positive for shortday plants) (1/hour)	0.245000
EM-FL Time between plant emergence and flower appearance (R1)(photothermal days)	19.500000
FL-SH Time between first flower and first pod (R3) (photothermal days)	7.900000
FL-SD Time between first flower and first seed (R5) (photothermal days)	14.800000
SD-PM Time between first seed (R5) and physiological maturity (R7)(photothermal days)	28.000000
FL-LF Time between first flower (R1) and end of leaf expansion (photothermal days)	26.000000
LFMAX Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, and high light(mg CO2/m2-s)	1.020000
SLAVR Specific leaf area of cultivar under standard growth conditions (cm2/g)	380.00000
SIZLF Maximum size of full leaf (three leaflets) (cm2)	180.00000
XFRT Maximum fraction of daily growth that is partitioned to seed + shell	1.000000
WTPSD Maximum weight per seed (g)	0.180000
SFDUR Seed filling duration for pod cohort at standard growth conditions (photothermal days)	21.000000
SDPDV Average seed per pod under standard growing conditions (#/pod)	2.200000
PODUR Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	14.000000

Fig. 1. Windows interface for users to import or input cultivar coefficients in RZWQM-CROPGRO.



Factors and Efficiencies

Soil Fertility Factor (0..1)	1
Soil Nitrification Factor (0..1)	1
Inoculation Efficiency (0..1)	1
N Fixation Efficiency (0..1)	1

Simulation Control

	On	Off
Water Routines	●	○
Nitrogen Routines	○	●
Symbiosis Routines	○	●
Phosphorous Routines	○	●
Potassium Routines	○	●
Disease and Pest Routines	○	●

Output Control

	Yes	No
Files named with Experiment code	○	●
Create Overview File	●	○
Create Summary File	●	○
Create Growth File	●	○
Create Carbon File	○	●
Create Water File	●	○
Create Nitrogen File	●	○
Create Mineral Nutrients File	○	●
Create Diseases/Pests File	○	●
Create Long Output File	●	○

Detailed Output Frequency (days): 1

DSSAT Treatment Number: 1

	Depth (cm)	Soil Root Growth Factor (SRGF)
1	5	1.00
2	15	1.00
3	30	0.17
4	45	0.14
5	60	0.14
6	90	0.19
7	120	0.25
8	150	0.21
9	179	0.10

Fig. 2. Windows interface for users to input simulation controls needed for CROPGRO.

ues. We paired the absolute differences (distances) between simulated and measured values from both models.

Table 1 lists the soil properties used in DSSAT-CROPGRO for all the data sets by their respective authors, along with the SRGF factors, and Table 2 lists the cultivar coefficients. For the Gainesville, FL study, the parameters were from DSSAT v3.5 (Tsuji et al., 1994; Hoogenboom et al., 1999). For the Akron, CO study, the parameters were from Ma et al. (2002) and Nielsen et al. (2002); however, we found that the DUL and LL values were too low in their papers when they were calculated from soil texture based on equations described in Ritchie et al. (1999). Therefore, we recalibrated the DSSAT-CROPGRO model based on field-measured DUL values and field-measured driest soil moisture contents during crop growing seasons for the Akron study (Table 1). Since soybean is a N fixer, simulation results are not affected by soil N status. Therefore, our evaluation efforts were focused on soil water and soybean production. The models were run from 1 January of each year.

RESULTS AND DISCUSSION

The Gainesville, Florida Study

Soil properties and cultivar coefficients are listed in Tables 1 and 2 and were used for the RZWQM-CROPGRO

Table 1. Soil properties used in DSSAT-CROPGRO and RZWQM-CROPGRO models.

	Rago silt loam					Millhopper fine sand			
Soil layer	New LL†# (RZWQM)	LL# (DSSAT)	DUL‡	SAT§	SRGF¶	LL	DUL	SAT	SRGF
m	$cm^3\ cm^{-3}$					$cm^3\ cm^{-3}$			
0.00–0.05	0.180	0.140	0.320	0.498	1.00	0.023	0.086	0.230	1.00
0.05–0.15	0.180	0.140	0.320	0.498	1.00	0.023	0.086	0.230	1.00
0.15–0.30	0.180	0.140	0.320	0.498	0.86	0.023	0.086	0.230	0.50
0.30–0.45	0.130	0.140	0.300	0.502	0.60	0.023	0.086	0.230	0.29
0.45–0.60	0.130	0.140	0.300	0.502	0.60	0.023	0.086	0.230	0.29
0.60–0.90	0.100	0.140	0.250	0.487	0.40	0.021	0.076	0.230	0.38
0.90–1.20	0.080	0.140	0.250	0.472	0.15	0.020	0.076	0.230	0.13
1.20–1.50	0.090	0.140	0.250	0.464	0.05	0.027	0.130	0.230	0.06
1.50–1.80	0.100	0.140	0.260	0.464	0.01	0.070	0.258	0.360	0.03

† LL, soil lower limit of plant available water.
‡ DUL, drained upper limit. DUL was assumed to be the wettest measured soil moisture in the field during crop growing seasons.
§ SAT, saturated water content.
¶ SRGF, root growth distribution factor.
# LL was calibrated based on the driest measured soil moisture in the field during crop growing seasons, which was 0.14, 0.13, 0.10, 0.08, 0.09, and 0.10 $cm^3\ cm^{-3}$ for soil depths of 0 to 30, 30 to 60, 60 to 90, 90 to 120, 120 to 150, and 150 to 180 cm, respectively.

hybrid model without modifications. Both models simulated very similar values for PET and actual ET (AET) (Fig. 3 and 4). Therefore, using a breeze of 100 km/d, the PET estimated by Shuttleworth–Wallace was similar to the Priestley–Taylor PET in the humid climate zone of Florida (Fig. 3). Both RZWQM-CROPRGO and DSSAT-CROPGRO models simulated lower water stresses at high water treatment than at low water treatment (Fig. 5). RZWQM did not simulate any runoff as expected with rain intensity estimated by assuming 2-h rainfall durations. However, the DSSAT model simulated 31 mm of runoff in 1978, 24 mm in 1979, and 0.5 mm in 1981 growing seasons. On average, DSSAT simulated 280 mm of water percolation compared with 292 mm simulated by RZWQM in the 1978 growing season. DSSAT simulated an average of 50 mm more percolation than RZWQM in the 1979 growing season. Average simulated percolation from both models was similar in the 1981 growing season. On average, DSSAT simulated 65 mm less PET and 47 mm less AET than RZWQM during the growing seasons. Simulated plant extractable water was very similar for both models (Fig. 6). On the average, DSSAT simulated only 7 mm more soil plant extractable water in 1978, 6 mm more in 1979, and 18 mm more in 1981 than RZWQM, which contributed to the slightly higher simulated water stress and lower yield in RZWQM-CROPGRO (Fig. 5, Table 3).

Simulated grain yield, biomass, pod yield, maximum LAI, and seed number at harvest are shown in Table 3 for both RZWQM-CROPGRO and DSSAT-CROPGRO models along with percentage differences between simulated and measured values. Root mean square errors (RMSEs) for biomass prediction were 307 kg ha^{-1} for DSSAT-CROPGRO and 499 kg ha^{-1} for RZWQM-CROPGRO. However, there was no significant difference in biomass prediction using a paired *t* test ($p = 0.497$). The RMSEs for seed yield prediction were 233 and 240 kg ha^{-1} for DSSAT-CROPGRO and RZWQM-CROPGRO, respectively, and no significant difference was observed ($p = 0.605$). The RMSEs for pod yield prediction were 238 and 316 kg ha^{-1} for DSSAT-CROPGRO and RZWQM-CROPGRO, respectively, with paired *t* test $p = 0.372$. The RMSEs for seed number prediction were 154 and 147 seeds m^{-2} for DSSAT-CROPGRO and RZWQM-CROPGRO, respectively. Again, no significant difference was found ($p = 0.381$) for seed number prediction. The RMSEs for maximum LAI prediction were 0.57 and 0.69 $cm^2\ cm^{-2}$ for DSSAT-CROPGRO and RZWQM-CROPGRO, respectively, with $p = 0.128$. Although the differences between DSSAT-CROPGRO and RZWQM-CROPGRO were not significant based on paired *t* test, DSSAT was slightly better in predicting crop growth than RZWQM-CROPGRO in terms of RMSEs when cultivar parameters were from DSSAT-

Table 2. Cultivar coefficient parameters used in both RZWQM-CROPGRO and DSSAT-CROPGRO models. See Fig. 1 for parameter definition.

	Akron (Pioneer 9291)	UFGA7801/UFGA7901 (Bragg)	UFGA8101 (Cobb)
Model parameters	From DSSAT	From DSSAT	From DSSAT
CSDL	13.59	12.33	12.25
PPSEN	0.249	0.32	0.33
EM-FL	20.0	19.5	21.0
FL-SH	6.0	10.0	9.0
FL-SD	13.5	15.0	16.0
SD-PM	20.0	36.8	37.0
FL-LF	26.0	19.0	18.0
LFMAX	1.0	1.0	1.03
SLAVR	250	355	375
SIZLF	180	170	190
XFRT	1.0	1.0	1.0
WTPSD	0.19	0.17	0.16
SFDUR	23.0	23.5	22.5
SDPDV	2.20	2.05	1.9
PODUR	8.0	10.0	10.0

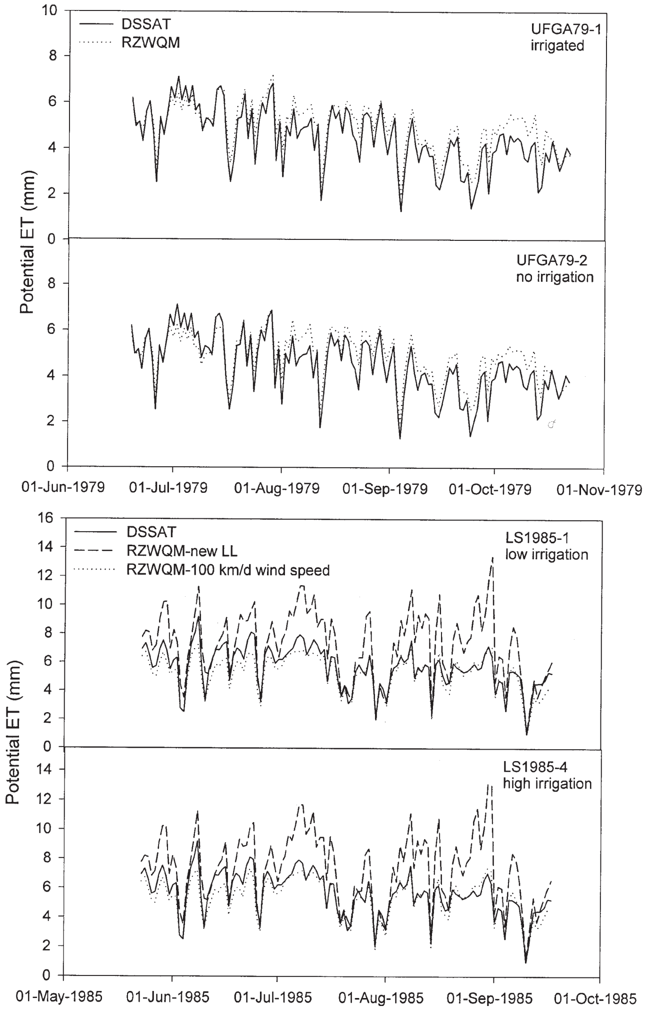


Fig. 3. Simulated potential evapotranspiration (PET) using RZWQM-CROPGRO and DSSAT-CROPGRO with examples from Gainesville, FL (above) and Akron, CO (below).

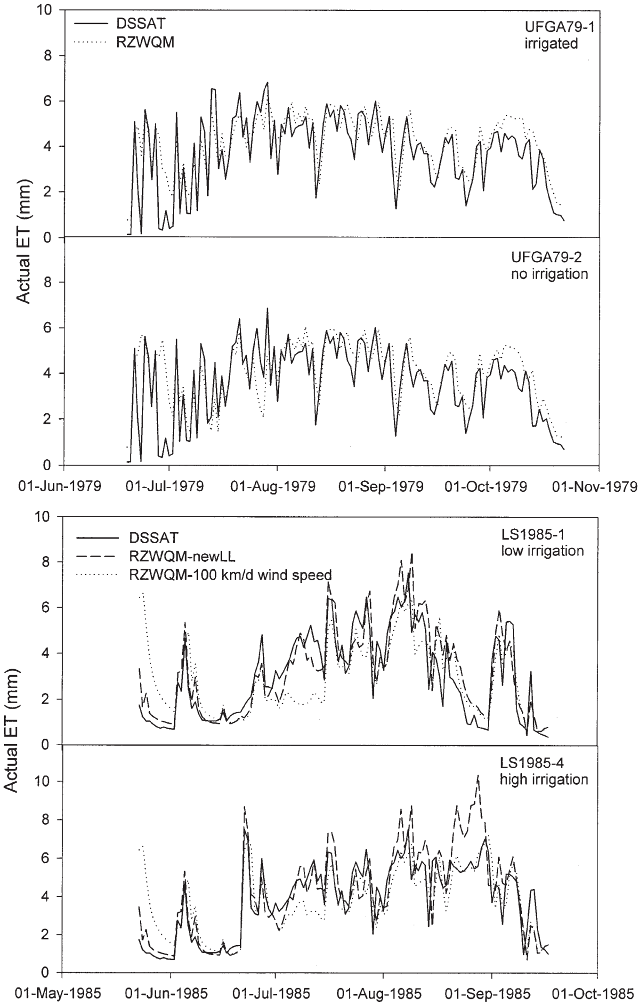


Fig. 4. Simulated actual evapotranspiration (AET) using RZWQM-CROPGRO and DSSAT-CROPGRO with examples from Gainesville, FL (above) and Akron, CO (below).

CROPGRO. However, since RZWQM-CROPGRO simulated slightly higher water stress than DSSAT-CROPGRO, some modifications to the soil properties in the RZWQM-CROPGRO hybrid model might improve simulation results as discussed later. Nonetheless, the hybrid model performed satisfactorily.

The Akron, Colorado Study

The DSSAT-CROPGRO model was recalibrated for the Akron study because of the lower DUL used by Ma et al. (2002) and Nielsen et al. (2002). Here we assumed that DUL was the wettest measured soil moisture in the field (Probert et al., 1998). However, when we used the measured driest soil moisture contents as LL as suggested by Probert et al. (1998), we found that DSSAT-CROPGRO simulated too high plant extractable water in the soil profile, and no yield response to irrigation treatments was simulated. Therefore, we used the measured driest soil moisture content in the top 30-cm soil layer (0.14 cm^3 cm^{-3}) as LL throughout the profile. Calibrated plant cultivar parameters are listed in Table 2.

In general, the recalibrated DSSAT-CROPGRO model provided better simulation of soil water contents (Fig. 7) than reported by Nielsen et al. (2002) for the top 60-cm soil profile and captured the initial high soil water contents observed in lower soil layers (90–180 cm) although the new soil parameters did not improve overall RMSE for soil water content simulation (e.g., 0.040 vs. 0.027 cm^3 cm^{-3} in Nielsen et al., 2002). The decrease in soil water content in lower soil layers (120–180 cm) could not be attributed to plant water uptake because of very small amount of root (or no root) in these layers but due to soil water redistribution as discussed later. The recalibrated DSSAT-CROPGRO model also provided better simulation of grain yield (Table 4) than using DUL estimated from soil texture, with RMSE of 125 kg ha^{-1} compared with 160 kg ha^{-1} in Nielsen et al. (2002). The model also simulated LAI and aboveground biomass well (Fig. 8), with RMSEs of 0.67 cm^3 cm^{-3} and 901 kg ha^{-1} compared with 0.83 cm^3 cm^{-3} and 908 kg ha^{-1} obtained by Nielsen et al. (2002). In calibrating DSSAT-CROPGRO, we also changed the SCS (Soil Conservation Service) runoff curve number so that no runoff was simulated. Nielsen et al. (2002) simulated a

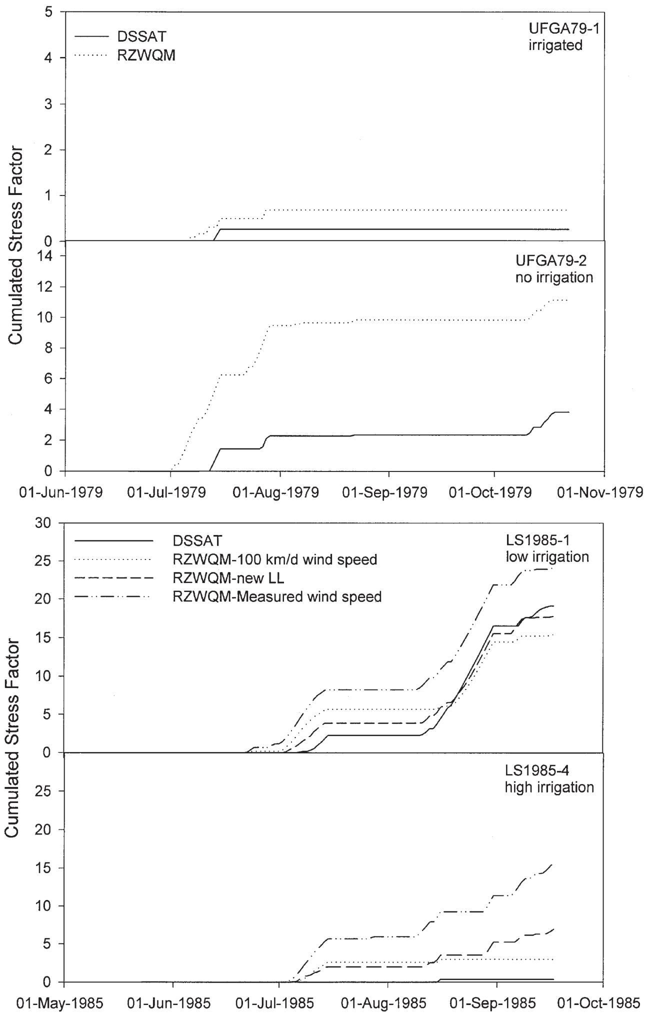


Fig. 5. Cumulated water stress factor for plant growth simulated by RZWQM-CROPGRO and DSSAT-CROPGRO with examples from Gainesville, FL (above) and Akron, CO (below) for two irrigation treatments.

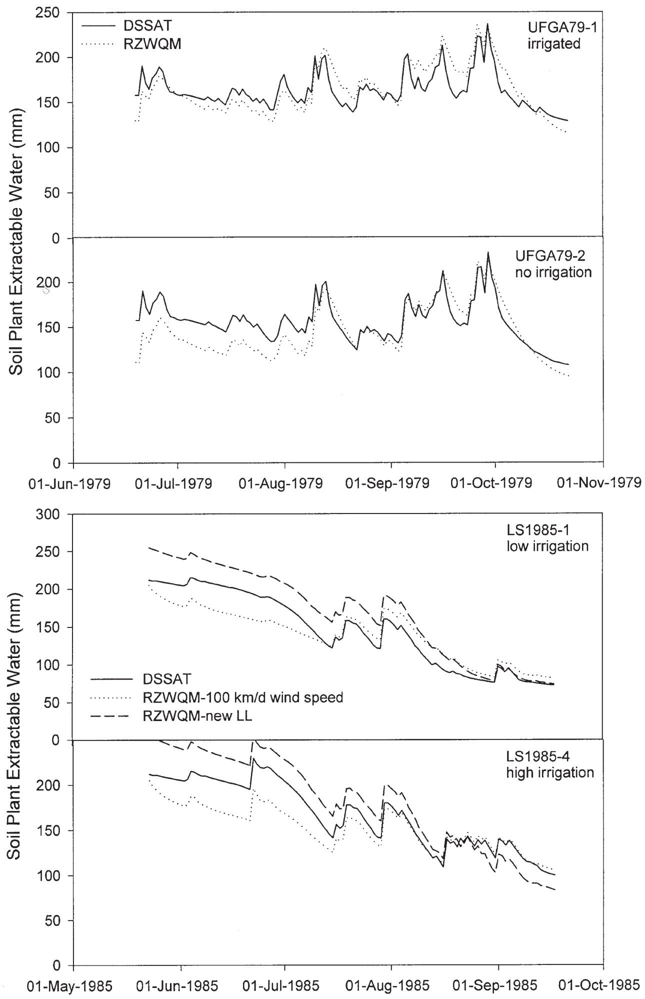


Fig. 6. Simulated soil plant extractable water by RZWQM-CROPGRO and DSSAT-CROPGRO with examples from Gainesville, FL (above) and Akron, CO (below).

cumulative runoff amount of 35 mm during the growing season, which was unlikely under semiarid Colorado conditions with close to zero slopes.

The above calibrated soil and plant parameters from DSSAT-CROPGRO model were directly used in RZWQM-CROPGRO by assuming DUL and LL to be soil moisture contents at 33 and 1500 kPa, respectively. Simulated grain yields were 25 to 50% lower than measured values (Table 4). This was partially due to simulated higher PET in RZWQM-CROPGRO than in DSSAT-CROPGRO under the semiarid Colorado condition (Fig. 3), 890 vs. 716 mm on average during the crop growing season, which resulted in higher simulated water stress factor in RZWQM-CROPGRO (Fig. 5). The Shuttleworth–Wallace PET used in RZWQM was tested by Farahani and Bausch (1995) and was shown to describe weather conditions in Colorado well. The simulated lower PET from Priestley–Taylor under Colorado conditions was expected because it did not consider wind effect and it was inadequate under dry, hot weather conditions (Federer et al., 1996). Predicted AET was similar from both models (421 mm for RZWQM-CROPGRPO and 434 mm for DSSAT-CROPGRO) (Fig. 4). No runoff was predicted from either model. Simulated water percolation was 3 mm in RZWQM and 0 mm in DSSAT-CROPGRO. DSSAT-CROPGRO was significantly better in yield simulation based on paired *t* test ($p < 0.001$).

Because of the higher PET simulated under the semiarid conditions using the Shuttleworth–Wallace approach, RZWQM-CROPGRO simulated higher water stress than DSSAT-CROPGRO (Fig. 5), which resulted in lower yield simulation (Table 4). As shown by Sau et al. (2004), using different PET in DSSAT crop models requires adjustment in some plant parameters. To test whether predicted lower yield was due to simulated high PET, we assumed 100 km/d wind speed as in the Gainesville, FL study, rather than using the measured wind speed in Akron, CO (average measured wind speed of 360 km/d). As shown in Fig. 3, simulated PET was similar to that of DSSAT-CROPGRO (average 649 mm during the growing seasons), and simulated yield was considerably improved with no significant differences between RZWQM and DSSAT ($p = 0.835$) when a breeze of 100 km/d wind speed was used

Table 3. Simulated soybean productions using DSSAT-CROPGRO and RZWQM-CROPGRO models for the Gainesville, FL study.

Treatment	Variables	Measured	DSSAT-CROPGRO	RZWQM-CROPGRO	Percentage of simulation error for DSSAT	Percentage of simulation error for RZWQM
1978-1, 155 mm irrigation	pod yield (kg ha^{-1})	4009	3734	3723	−6.86	−7.13
	seed yield (kg ha^{-1})	3041	2841	2795	−6.58	−8.09
	seed number (no. m^{-2})	2223	1991	2125	−10.44	−4.41
	maximum LAI† (cm^2 cm^{-2})	4.67	4.90	5.46	4.93	16.92
	harvested biomass (kg ha^{-1})	6068	5778	5932	−4.78	−2.24
1978-2, no irrigation	pod yield (kg ha^{-1})	1602	1485	1713	−7.30	6.93
	seed yield (kg ha^{-1})	1178	1120	1262	−4.92	7.13
	seed number (no. m^{-2})	969	833	1017	−14.04	4.95
	maximum LAI (cm^2 cm^{-2})	4.50	4.88	5.15	8.44	14.44
	harvested biomass (kg ha^{-1})	3491	3153	3485	−9.68	−0.17
1979-1, 85 mm irrigation	pod yield (kg ha^{-1})	3734	3742	3886	0.21	4.07
	seed yield (kg ha^{-1})	2891	2961	3076	2.42	6.40
	seed number (no. m^{-2})	1765	1950	2030	10.48	15.01
	maximum LAI (cm^2 cm^{-2})	4.71	5.41	5.52	14.86	17.20
	harvested biomass (kg ha^{-1})	5781	6147	6368	6.33	10.15
1979-2, no irrigation	pod yield (kg ha^{-1})	3755	3706	3484	−1.30	−7.22
	seed yield (kg ha^{-1})	2883	2932	2756	1.70	−4.41
	seed number (no. m^{-2})	1827	1930	1797	5.64	−1.64
	maximum LAI (cm^2 cm^{-2})	4.36	5.04	3.69	15.60	−15.37
	harvested biomass (kg ha^{-1})	5534	5789	4957	4.61	−10.43
1981-1, 237 mm full irrigation	pod yield (kg ha^{-1})	4526	4627	4497	2.23	−0.64
	seed yield (kg ha^{-1})	3502	3650	3496	4.23	−0.17
	seed number (no. m^{-2})	2374	2266	2344	−4.55	−1.26
	maximum LAI (cm^2 cm^{-2})	6.25	5.60	5.63	−10.40	−9.92
	harvested biomass (kg ha^{-1})	6851	6720	6478	−1.91	−5.44
1981-2, 155 mm irrigation with vegetative stress	pod yield (kg ha^{-1})	4403	4280	3765	−2.79	−14.49
	seed yield (kg ha^{-1})	3355	3357	2890	0.06	−13.86
	seed number (no. m^{-2})	2195	2065	2065	−5.92	−5.92
	maximum LAI (cm^2 cm^{-2})	4.48	3.94	3.81	−12.05	−14.96
	harvested biomass (kg ha^{-1})	6109	5747	5161	−5.93	−15.52
1981-3, 199 mm irrigation with reproductive stress	pod yield (kg ha^{-1})	3690	4219	4007	14.34	8.59
	seed yield (kg ha^{-1})	2738	3264	3005	19.21	9.75
	seed number (no. m^{-2})	2119	2264	2344	6.84	10.62
	maximum LAI (cm^2 cm^{-2})	6.25	5.60	5.63	−10.40	−9.92
	harvested biomass (kg ha^{-1})	5881	6217	5978	5.71	1.65

† LAI, leaf area index.

Table 4. Simulated soybean seed yield using DSSAT-CROPGRO and RZWQM-CROPGRO models for the Akron, CO study.

				RZWQM-CROPGRO (LL† from DSSAT)					
		DSSAT-CROPGRO		Measured wind speed		100 km/d wind speed		With modified LL	
Treatment	Measured (±standard error)	Value	Percentage error	Value	Percentage error	Value	Percentage error	Value	Percentage error
	kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%
LS1985-1	1287 (±52)	1259	−2.18	963	−25.17	1486	15.46	1385	7.61
LS1985-2	1646 (±149)	1464	−11.06	1058	−35.72	1727	4.92	1545	−6.14
LS1985-3	2369 (±115)	2407	1.60	1450	−38.79	2338	−1.31	2036	−14.06
LS1985-4	2678 (±9)	2764	3.21	1701	−36.48	2514	−6.12	2384	−10.98
LS1986-1	595 (±47)	554	−6.89	411	−30.92	646	8.57	764	28.40
LS1986-2	967 (±115)	783	−19.03	535	−44.67	882	−8.79	923	−4.55
LS1986-3	1534 (±426)	1709	11.41	777	−49.35	1560	1.69	1478	−3.65
LS1986-4	2135 (±516)	2266	6.14	1172	−45.11	2345	9.84	2171	1.69

† LL, soil lower limit of plant available water.

(Table 4). Average cumulated AET was 410 mm during the growing seasons (Fig. 4). Although the simulated lower PET reduced water stress considerably (Fig. 5) and improved yield simulation (Table 4), simulations of LAI and aboveground biomass were considerably lower than field observations (Fig. 8). Therefore, some adjustments were needed to account for the simulated higher PET in RZWQM-CROPGRO model for the Akron, CO study.

To improve simulation results using RZWQM-CROPGRO hybrid model with the simulated higher PET from the Shuttleworth–Wallace method, we evaluated the possibility of using a different LL. The reason was that, in RZWQM-CROPGRO, LL was used both as the lower limit of plant available water and as the soil water content at 1500 kPa. The latter determined soil water movement in the soil. Theoretically, the LL and the LL15 should be treated differently because LL15 is a soil property and LL is determined by both soil and plant properties. To demonstrate the effect of LL on RZWQM-CROPGRO simulations, we used the field-measured driest soil moisture contents as LL for all the soil layers except the top 30 cm (Table 1). The LL for the top 30 cm soil layer was calibrated to 0.18 cm^3 cm^{-3} to improve soil water simulations in that layer (Fig. 7). The lower LLs for subsurface soil layers increased available soil water in the soil profile (Fig. 6) and improved yield prediction (Table 4). No significant differences in simulated yields were found between DSSAT-CROPGRO and RZWQM-CROPGRO with the new LLs ($p = 0.635$). Slight improvement was observed in LAI and aboveground biomass simulations

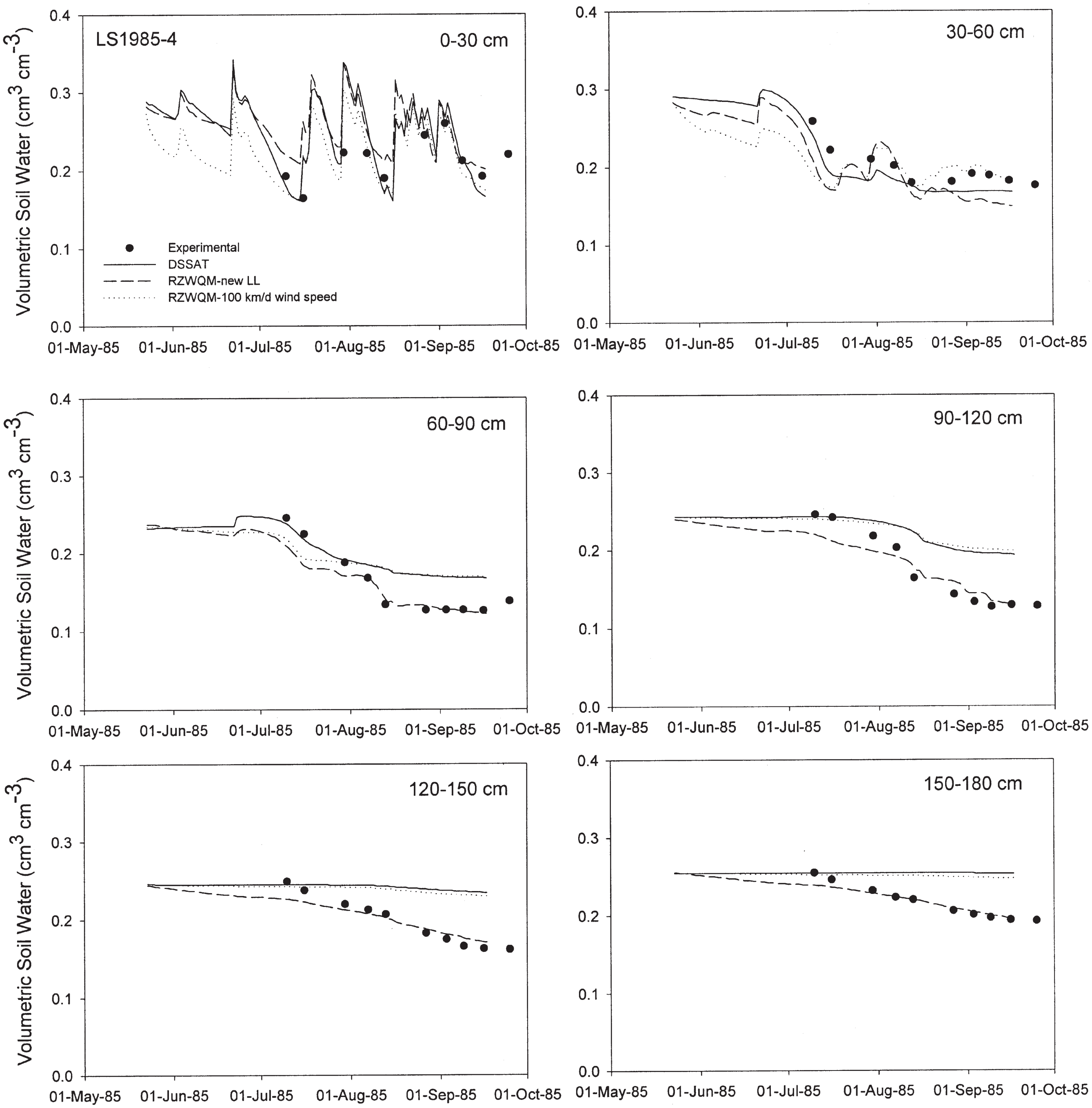


Fig. 7. Predicted and measured soil water contents for the wettest treatment in 1985 (LS1985-4) in the Akron, CO study by RZWQM-CROPGRO and DSSAT-CROPGRO.

when the new LLs were used (Fig. 8). Simulated average PET and AET were 907 and 448 mm, respectively.

The new LLs not only improved crop simulations (Table 4 and Fig. 8), but also improved soil water simulation (Fig. 7), especially for the lower soil layers (60–180 cm). Simulated RMSE of RZWQM-CROPGRO with the new LLs was 0.026 cm^3 cm^{-3}. It also simulated about 2 mm of surface runoff and 21 of mm drainage. As shown in Fig. 7, no difference was found in soil water simulations below 90 cm between DSSAT-CROPGRO and RZWQM-CROPGRO with 100 km/d wind speed. Therefore, the different water balance approaches (Richards' equation vs. tipping-bucket) only had effects for upper soil layer where soil water was more dynamic. However, by adjusting the LLs, RZWQM-CROPGRO was able to simulate better soil water content and soybean yield. Simulation results could be further improved if we differentiated LL and LL15 in the model as in the APSIM model (Probert et al., 1998).

SUMMARY AND CONCLUSIONS

In this study, we evaluated the RZWQM-CROPGRO hybrid model against the original DSSAT-CROPGRO model for their performance in predicting soybean responses to various irrigation treatments using experi-

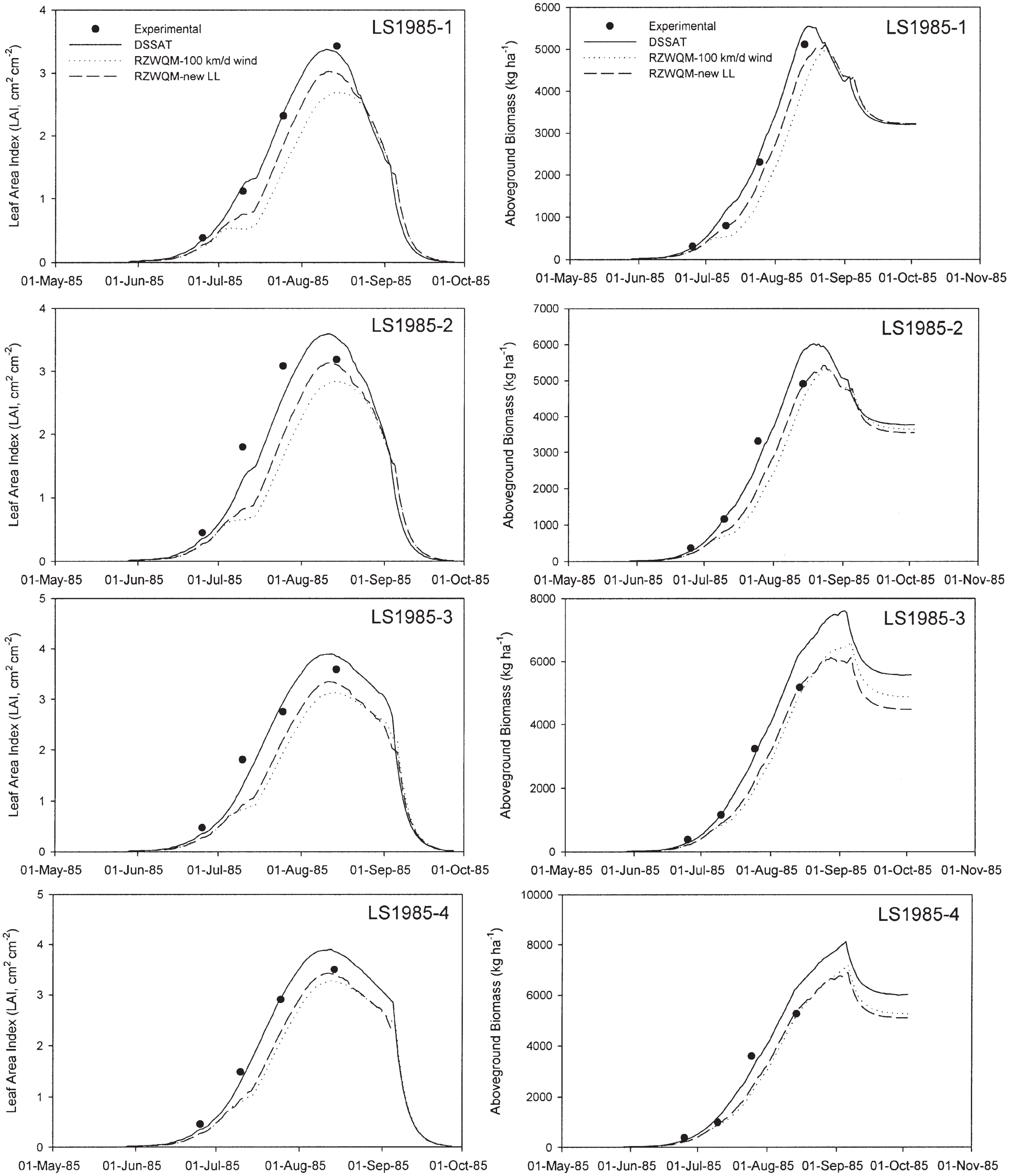


Fig. 8. Predicted and measured leaf area index (LAI) and aboveground biomass for the Akron, CO study by RZWQM-CROPGRO and DSSAT-CROPGRO.

mental data sets from Akron, CO and Gainesville, FL under different weather, soil, and management conditions. All the experiments included some type of irrigation management. Both models were compared for simulations of soil water content, LAI, final grain yield, aboveground biomass, pod yield, and seed number at harvest maturity. Under the humid Florida weather conditions, the RZWQM-CROPGRO model provided a similar prediction of soybean growth using the cultivar parameters derived from DSSAT-CROPGRO. However, for the semiarid Colorado conditions, PET estimated by RZWQM was much higher than PET simulated by DSSAT. Therefore, RZWQM-CROPGRO simulated much higher water stress and lower soybean yield when soil and plant parameters were derived from the original DSSAT system. Reducing PET by assuming a 100 km/d wind speed in RZWQM-CROPGRO provided comparable simulation results with those from DSSAT-CROPGRO model. The study also demonstrated that, using the simulated high PET and calibrating LL, RZWQM-CROPGRO was able to provide good simulations for both soybean growth and soil water balance. Another possible way to improve simulation results, when simulated PET is different between RZWQM and DSSAT models, is to recalibrate some cultivar coefficients since RZWQM-CROPGRO hybrid model is a new model and previously calibrated cultivar coefficients have inherited genotype × environment (G × E) interactions (McMaster et al., 2003).

Although simulation results from the RZWQM-CROPGRO hybrid model did not show much improvement over the original DSSAT-CROPGRO model in terms of soybean production, the use and application of RZWQM-CROPGRO hybrid model has some other advantages, such as macropore flow, tile flow, pesticide movement, water table, detailed soil C/N dynamics, and agricultural management effects. DSSAT users have expressed the need for incorporating tile-drain flow (Shen et al., 1998; Garrison et al., 1999), a water table (Gerakis and Ritchie, 1998), pesticide leaching (Gerakis and Ritchie, 1998), tillage (Andales et al., 2000), and better C/N dynamics (Gijsman et al., 2002) into the DSSAT simulation models. This hybrid model will greatly expand the application range of CROPGRO model under different experimental conditions. On the other hand, it will give RZWQM users an option of a new plant growth module.

This study also demonstrated that linking modules to form new models is not simply a computer exercise. When one module is replaced with another one, some changes in model structure or parameters may have to be made so that the new model would give realistic simulation results. This is because the modules in the original model are partly dependent on each other to function properly. A replacement module has to develop the right relationship with other modules in the new model. In our case, we replaced the tipping-bucket approach in DSSAT with Richards' equation in RZWQM and Priestley–Taylor PET in DSSAT with Shuttleworth–Wallace PET in RZWQM. Those substitutes resulted in higher PET calculation and higher water stress being calculated. As a result, without making corresponding changes to water stress effects on plant physiological processes in the CROPGRO model, the RZWQM-CROPGRO hybrid model simulated lower yield and biomass, unless some adjustments were made to reflect the difference of the new substitutes. Future work on the RZWQM-CROPGRO hybrid model would include defining new water stress factors, differentiating the LL from LL15, and testing the hybrid model under different soil and climate conditions with soil properties independently estimated by RZWQM based on Rawls et al. (1982).

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