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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Published in Agron. J. 97:1172–1182 (2005).
Modeling
doi:10.2134/agronj2003.0314

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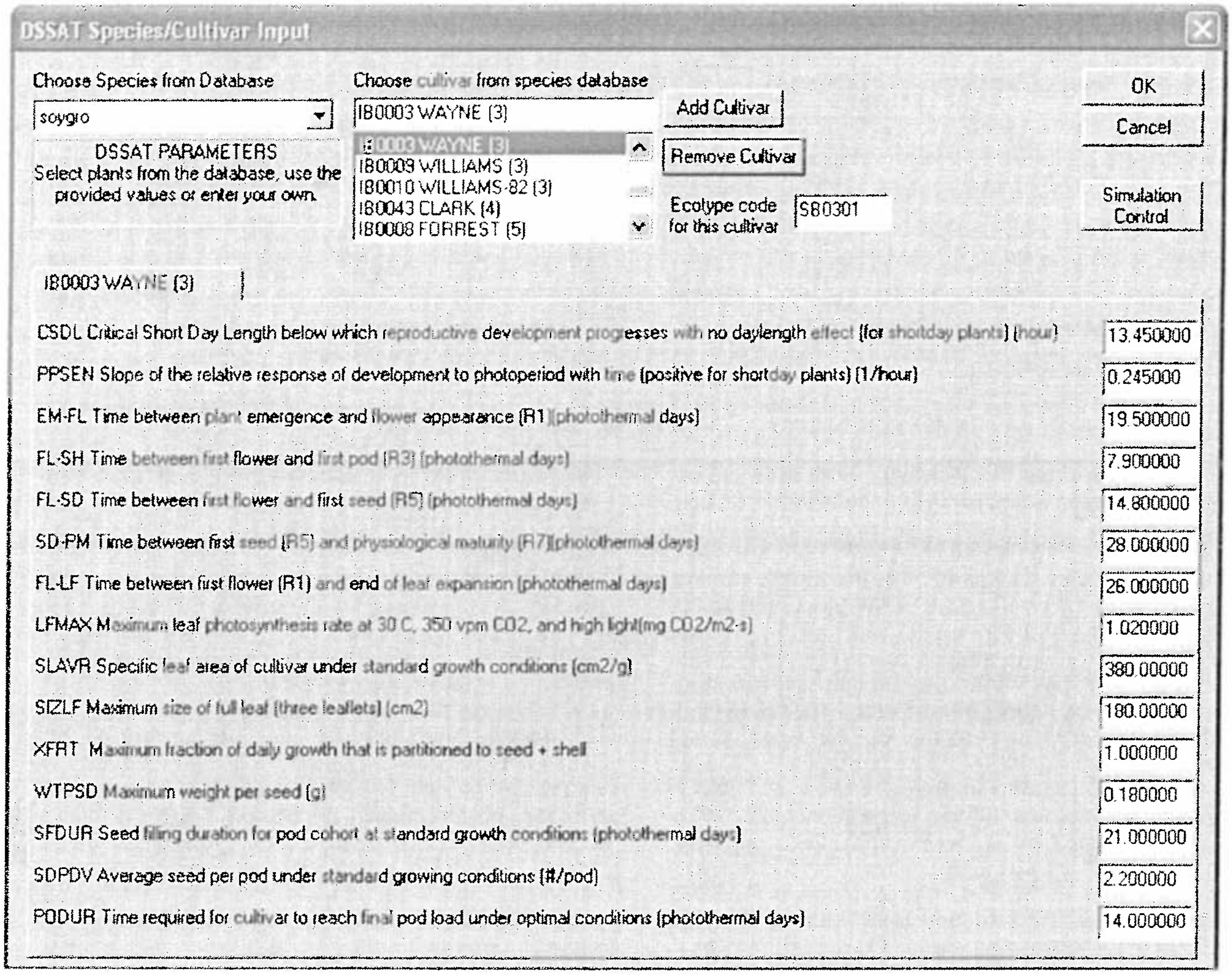
Abbreviations: AET, actual evapotranspiration; DSSAT, Decision Support System for Agrotechnology Transfer; DUL, drained upper limit; LAI, leaf area index; LL, soil lower limit of plant available water; LL15, 1500 kPa soil water content; PET, potential evapotranspiration; RMSE, root mean square error;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



Choose Species from Database: soygro

DSSAT PARAMETERS
Select plants from the database, use the provided values or enter your own.

Choose cultivar from species database: IB0003 WAYNE (3)

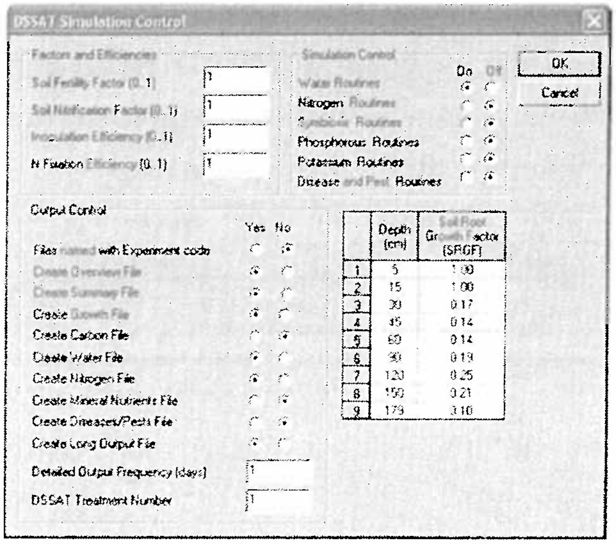
- IB0003 WAYNE (3)
- IB0009 WILLIAMS (3)
- IB0010 WILLIAMS-82 (3)
- IB0043 CLARK (4)
- IB0008 FORREST (5)

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

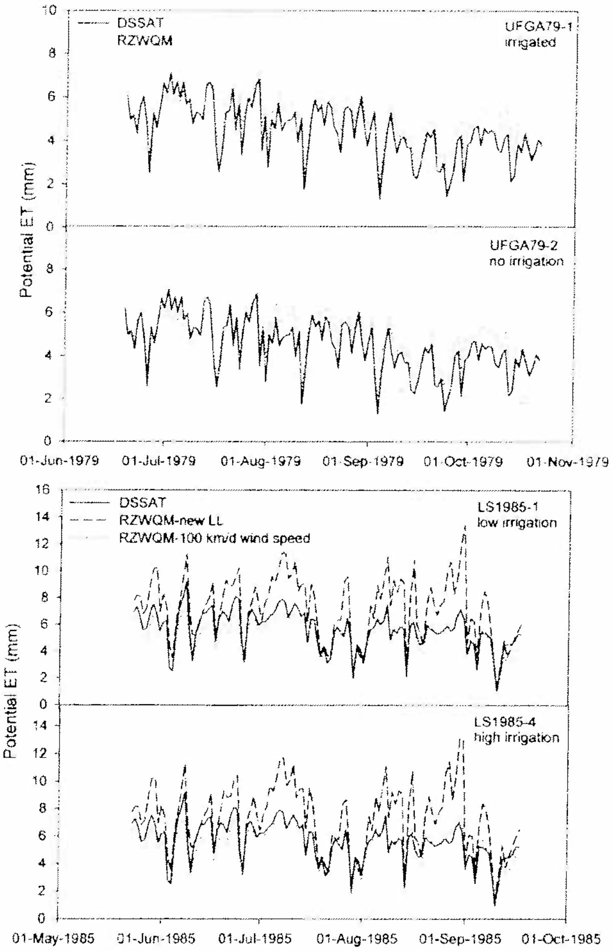


Fig. 3. Simulated potential evapotranspiration (PET) using RZWQM-CROPGRO and DSSAT-CROPGRO with examples from Gainesville, FL (above) and Akron, CO (below).

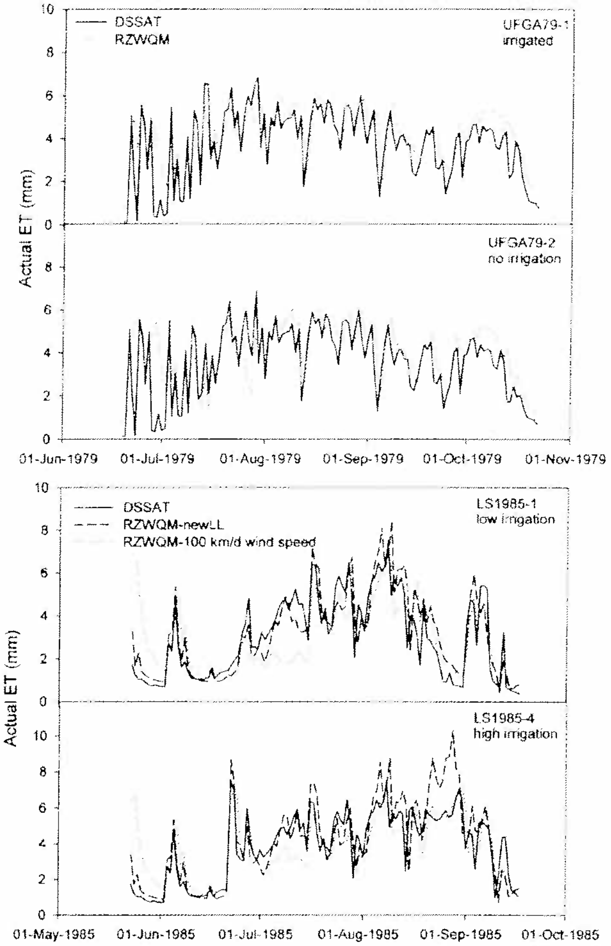


Fig. 4. Simulated actual evapotranspiration (AET) using RZWQM-CROPGRO and DSSAT-CROPGRO with examples from Gainesville, FL (above) and Akron, CO (below).

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

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

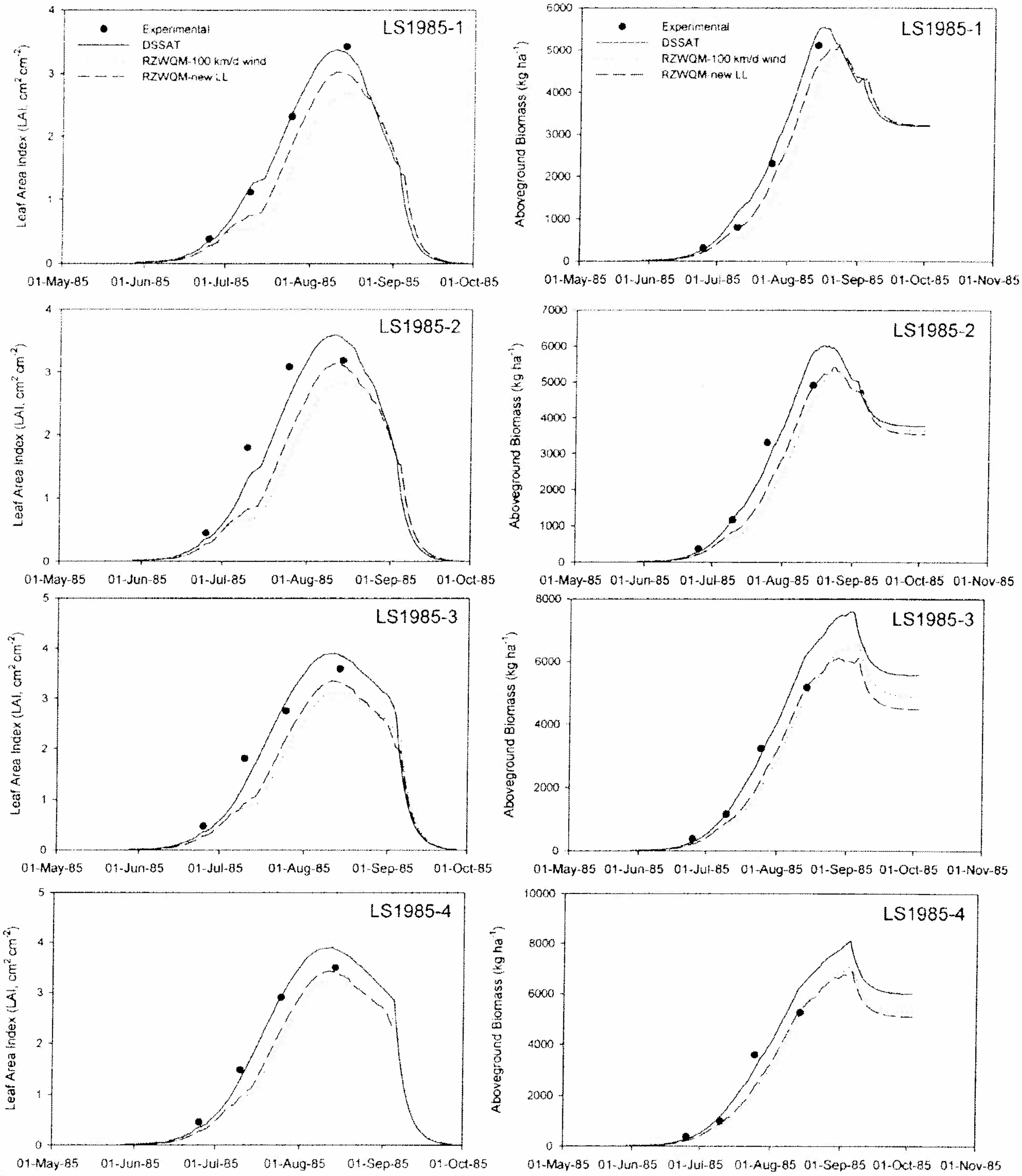


Fig. 8. Predicted and measured leaf area index (LAI) and aboveground biomass for the Akron, CO study by RZWQM-CROPGRO and DSSAT-CROPGRO.

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. How-

port System for Agrotechnology Transfer (DSSAT) v.3. Vol. 4. Univ. of Hawaii, Honolulu.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. DSSAT Cropping System Model. Eur. J. Agron. 18: 235–265.

Ma, L., G. Hoogenboom, L.R. Ahuja, J.C. Ascough, II, and S.A. Saseendran. 2005. Evaluation of the RZWQM-CERES-Maize hybrid model for maize production. Agric. Syst. (in press).

Ma, L., D.C. Nielsen, L.R. Ahuja, J.R. Kiniry, J.D. Hanson, and G. Hoogenboom. 2002. An evaluation of RZWQM, CROPGRO, and CERES-maize for responses to water stress in the Central Great Plains of the U.S. p. 119–148. *In* L.R. Ahuja, L. Ma, and T.A. Howell (ed.) Agricultural system models in field research and technology transfer. Lewis Publ., Boca Raton, FL.

Ma, L., D.C. Nielsen, L.R. Ahuja, R.W. Malone, S.A. Saseendran, K.W. Rojas, J.D. Hanson, and J.G. Benjamin. 2003. Evaluation of RZWQM under varying irrigation levels in Eastern Colorado. Trans. ASAE 46:39–49.

Ma, L., and M.J. Shaffer. 2001. A review of carbon and nitrogen processes in nine U.S. soil nitrogen dynamics models. p. 55–102. *In* M.J. Shaffer, L. Ma, and S. Hansen (ed.) Modeling carbon and nitrogen dynamics for soil management. Lewis Publ., Boca Raton, FL.

McCown, R.L., B.A. Keating, P.S. Carberry, Z. Hochman, and D. Hargreaves. 2002. The co-evolution of the agricultural production systems simulator (APSIM) and its use in Australian dryland cropping research and farm management intervention. p. 149–175. *In* L.R. Ahuja, L. Ma, and T.A. Howell (ed.) Agricultural system models in field research and technology transfer. CRC Press, Boca Raton, FL.

McGechan, M.B., and L. Wu. 2001. A review of carbon and nitrogen processes in European soil nitrogen dynamics models. p. 103–171. *In* M.J. Shaffer, L. Ma, and S. Hansen (ed.) Modeling carbon and nitrogen dynamics for soil management. Lewis Publ., Boca Raton, FL.

McMaster, G.S., J.C. Ascough, II, M.J. Shaffer, L.A. Deer-Ascough, P.F. Byrne, D.C. Nielsen, S.D. Haley, A.A. Andales, and G.H. Dunn. 2003. GPFARM plant model parameters: Complications of varieties and the genotype × environment interaction in wheat. Trans. ASAE 46:1337–1346.

Nielsen, D.C. 1990. Scheduling irrigations for soybeans with the crop water stress index (CWSI). Field Crops Res. 23:103–116.

Nielsen, D.C. 1997. Water use and yield of canola under dryland conditions in the central Great Plains. J. Prod. Agric. 10:307–313.

Nielsen, D.C., L. Ma, L.R. Ahuja, and G. Hoogenboom. 2002. Simulating soybean water stress effects with RZWQM and CROPGRO models. Agron. J. 94:1234–1243.

Priestley, C.H.B., and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100:81–92.

Probert, M.E., J.P. Dimes, B.A. Keating, R.C. Dalal, and W.M. Strong. 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agric. Syst. 56: 1–28.

Rawls, W.J., D.L. Brakensiek, and K.E. Saxton. 1982. Estimation of soil water properties. Trans. ASAE 25:1316–1320, 1328.

Reddy, K.R., V.G. Kakani, J.M. McKinion, and D.N. Baker. 2002. Applications of cotton simulation model, GOSSYM, for crop management, economic, and policy decisions. p. 33–54. *In* L.R. Ahuja, L. Ma, and T.A. Howell (ed.) Agricultural system models in field research and technology transfer. CRC Press, Boca Raton, FL.

Ritchie, J.T. 1998. Soil water balance and plant water stress. p. 41–54. *In* G.Y. Tsuji, G. Hoogenboom, and P.K. Thornton (ed.) Understanding options for agricultural production. Kluwer Academic Publ., Dordrecht, the Netherlands.

Ritchie, J.T., A. Gerakis, and A. Suleiman. 1999. Simple model to estimate field-measured soil water limits. Trans. ASAE 42:1609–1614.

Rojas, K.W., L. Ma, J.D. Hanson, and L.R. Ahuja. 2000. RZWQM98 user interface. p. 327–364. *In* L.R. Ahuja, K.W. Rojas, J.D. Hanson, M.J. Shaffer, and L. Ma (ed.) Root Zone Water Quality Model. Water Resour. Publ., Highland Ranch, CO.

Saseendran, S.A., D.C. Nielsen, L. Ma, L.R. Ahuja, and A.D. Halvorson. 2004. Modeling nitrogen management effects on winter wheat production using RZWQM and CERES-wheat. Agron. J. 96:615–630.

Sau, F., K.J. Boote, W.M. Bostick, J.W. Jones, and M.I. Minguez. 2004. Testing and improving evapotranspiration and soil water balance of the DSSAT crop models. Agron. J. 96:1243–1257.

Shen, J., W.D. Batchelor, J.W. Jones, J.T. Ritchie, R.S. Kanwar, and C.W. Mize. 1998. Incorporation of a subsurface tile drainage component into a soybean growth model. Trans. ASAE 41:1305–1313.

Shuttleworth, W.J., and J.S. Wallace. 1985. Evaporation from sparse crops—an energy combination theory. Q. J. R. Meteorol. Soc. 111:839–855.

Timlin, D., Y. Pachepskey, F. Whisler, and V. Reddy. 2002. Experience with on-farm applications of GLYCIM/GUICS. p. 55–69. *In* L.R. Ahuja, L. Ma, and T.A. Howell (ed.) Agricultural system models in field research and technology transfer. CRC Press, Boca Raton, FL.

Tsuji, G.Y., A. duToit, A. Jintrawet, J.W. Jones, W.T. Bowen, R.M. Ogoshi, and G. Uehara. 2002. Benefits of models in research and decision support: The IBSNAT experience. p. 71–89. *In* L.R. Ahuja, L. Ma, and T.A. Howell (ed.) Agricultural system models in field research and technology transfer. CRC Press, Boca Raton, FL.

Tsuji, G.Y., G. Uehara, and S. Balas. 1994. Decision Support System for Agrotechnology Transfer (DSSAT) v3. Univ. of Hawaii, Honolulu.