Simulating Soybean Water Stress Effects with RZWQM and CROPGRO Models

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ABSTRACT

The Root Zone Water Quality Model (RZWQM) and CROPGRO-Soybean simulate soybean [*Glycine max* (L.) Merr.] growth, development, and yield. The models require calibration for soybean grown in the specific environmental conditions of the central Great Plains before any long-term assessments can be made of dryland soybean yield potential under the highly variable precipitation patterns of this area. The objective of this study was to calibrate and test RZWQM and CROPGRO-Soybean for soybean growth, yield, and water use under a range of water stress conditions normally encountered by dryland production systems in the central Great Plains. Data from five experiments, each with four levels of water availability (20 data sets), were used to evaluate leaf area, plant height, aboveground biomass, evapotranspiration (ET), soil water extraction, and yield of soybean. Data from one water level of one experiment was used to calibrate the models, and the other 19 data sets were used as evaluation data sets. Both models correctly predicted the time course of volumetric water content, leaf area development, and plant and height biomass increase although RZWQM more accurately simulated water extraction in the lower soil profile. The decline in ET that is a result of decreased water availability was generally predicted well by both models. The models generally estimated the yield to within 10 to 15% of measured values. The models should be useful tools in evaluating the potential for soybean as an alternative crop in dryland rotations in the central Great Plains.

The central Great Plains have traditionally been an area of wheat (*Triticum aestivum* L.)–fallow production in which one crop is grown every 2 yr. Wheat–fallow was devised as a production system to minimize the impact of highly variable precipitation on grain production (Greb, 1983). Use of no-till production methods improves precipitation storage efficiency and soil water availability, which allow for more intense and diversified cropping systems (Halvorson et al., 1994; Peterson et al., 1993; Anderson et al., 1999; Nielsen et al., 1999).

Crop production models, such as the ones used within the Root Zone Water Quality Model (RZWQM) (Ahuja et al., 2000a) and the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 1999; Jones et al., 1998; Tsuji et al., 1994), may find important uses in predicting crop growth and yield under varying soil and weather conditions, thereby determining the most advantageous crop sequencing for dryland rotations in the central Great Plains. Also, interest is growing in diversifying crop production by expanding the range of soybean production into dryland (nonirrigated) areas of the central Great Plains. The RZWQM and DSSAT could be used to predict success or failure of soybean in dryland crop rotations. But for a crop model to be a valuable aid in predicting the effects, and success or failure, of intensifying and diversifying rotations and using new crops, it must be able to adequately respond to varying degree and timing of water stress (Tsuji et al., 1998).

Several recent reports have described the performance of the generic crop production model (Hanson, 2000) used in the RZWQM (Landa et al., 1999; Wu et al., 1999; Jaynes and Miller, 1999; Martin and Watts, 1999; Ghidey et al., 1999; Nokes et al., 1996). These studies describe the model parameterized for corn (*Zea mays* L.) and soybean from the Management Systems Evaluation Areas (MSEA) projects. An advantage of a generic crop model is that it can be parameterized for different crops without a detailed knowledge of crop growth, especially by those who are not plant physiologists. A disadvantage of a generic plant model is that it does not provide detailed simulations of phenology and yield component development.

The RZWQM simulates plant biomass, crop yield, leaf area index (LAI), and plant height but is not designed to simulate detailed phenology. An individual plant's life cycle is divided into seven stages: dormant, germination, emergence, four leaf, vegetative growth, reproductive growth, and senescence. Progression from one growth stage to another is a constant that is modified by environmental stresses (temperature, N, and moisture). One distinguishing feature of the RZWQM plant growth model is the population development. Not all of the plants are in the same growth stage at a given time. A modified Leslie probability matrix is used in the model to describe the fate of a plant (Leslie, 1945; Usher, 1966). A plant can (i) advance to the next growth stage after meeting the minimum growth requirement (minimum days modified by environmental stresses), (ii) stay in the same class, or (iii) die (Hanson, 2000). The RZWQM calculates soil evaporation and plant transpiration based on an extended Shuttleworth–Wallace evapotranspiration (ET) model (Farahani and DeCoursey, 2000). This model is an extension of the Penman–Montieth method. Actual rates of soil evaporation and canopy transpiration are functions of the soil water transport and crop growth components of RZWQM. Soil evaporation is determined by the ability of the soil to deliver the potential rate as determined using the Richards' equation. The root water uptake function of Nimah and Hanks (1973) acts as a sink term in the Richards' equation and

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Abbreviations: DSSAT, Decision Support System for Agrotechnology Transfer; Drip, drip irrigation experiment; EEWP, effect of water fitness; ET, evapotranspiration; EWP, water fitness; LAI, leaf area index; LS, line-source gradient irrigation experiment; MSEA, Management Systems Evaluation Areas; RO, rainout shelter experiment; RZWQM, Root Zone Water Quality Model.

determines the actual rate of crop transpiration with upper limits defined by the potential transpiration rate. The Green–Ampt equation is used to estimate water infiltration during rainfall or irrigation events (Ahuja et al., 2000b). Photosynthesis rate is reduced by water stress in RZWQM in proportion to the ratio of actual to potential transpiration.

Farahani et al. (1999) worked with RZWQM under the environmental conditions of eastern Colorado. They reported that RZWQM overpredicted dryland corn yields by 21% on a summit site, underpredicted dryland corn yields by 23% at a toe slope position, and underpredicted irrigated corn yields by 12%. Martin and Watts (1999) reported that RZWQM overestimated irrigated corn yields in central Nebraska by 60%. Nokes et al. (1996) found that RZWQM overestimated Ohio corn yields by only 8 to 11% after calibration. Soybean yield depression due to abnormally wet conditions was accurately estimated by RZWQM in Iowa (Jaynes and Miller, 1999). Ghidey et al. (1999) reported an approximately 15% overprediction of soybean yield in Missouri by RZWQM when yields were greater than 1500 kg ha^{-1}, but the model underestimated soybean yield by more than 30% when conditions were very dry and yields were low.

CROPGRO is a dynamic simulation model that simulates growth and development for a wide range of leguminous crops. Current crops include soybean, peanut (*Arachis hypogaea* L.), dry bean (*Phaseolus vulgaris* L.), cowpea (*Vigna unguiculata* L.), and chickpea (*Cicer arietinum* L.) (Boote et al., 1998a). In addition, the model can simulate growth of other crops such as tomato (*Lycopersicon esculentum* L.), pepper (*Capsicum annuum* L.), and bahiagrass (*Paspalum notatum*). The model operates on a daily time step while some internal processes, such as the calculation of development and photosynthesis, are handled at an hourly time step. CROPGRO simulates vegetative and reproductive development as a function of temperature, photoperiod, and interaction with drought and other stress factors. The model predicts the number of nodes on the main stem, canopy height, canopy width, rooting depth, and the occurrence of each growth phase, including germination, emergence, flower initiation, anthesis, occurrence of first pod and first seed, physiological maturity, and harvest maturity (Boote et al., 1998b)

CROPGRO has a detailed C balance that simulates gross photosynthesis, maintenance and growth respiration, and partitioning to the individual plant components. Plant composition, including N and protein concentration, is calculated for leaves, stems, petioles, seeds, shells, pods, and roots. Leaf senescence is a function of crop age, drought stress, distribution of light in the canopy, and extreme events such as a freeze. The model calculates potential ET based on the Priestley–Taylor equation (Priestley and Taylor, 1972). Soil water movement is based on a one-dimensional soil profile and uses a cascading approach (Ritchie, 1998). The model also simulates a plant and soil N balance, including N fixation for the grain legumes, N uptake, N mobilization, and other related processes (Godwin and Singh, 1998). Both the soil water and N balance are similar to the CERES model (Ritchie et al., 1998).

The processes in CROPGRO that are sensitive to water deficit include photosynthesis, transpiration, N_2 fixation, leaf area increase, vegetative stage progress, internode elongation, and partitioning to roots (Boote et al., 1998b; Ritchie, 1998). When root water uptake is unable to meet transpirational demand of the foliage, then photosynthesis and transpiration are reduced in direct proportion to decreased water uptake.

CROPGRO is part of DSSAT (Hoogenboom et al., 1999; Tsuji et al., 1994). The DSSAT crop simulation models (Hoogenboom et al., 1994) use standard input files for weather and soil conditions as well as crop management (Jones et al., 1994). The DSSAT also includes a wide range of application programs for seasonal analysis (Thornton and Hoogenboom, 1994), crop rotation and sequence analysis (Thornton et al., 1995), and spatial analysis at a field or a regional scale (Engel et al., 1997; Thornton et al., 1997). CROPGRO has been evaluated for a wide range of applications, not only in the USA, but also in many other countries (Alagarswamy et al., 2000; Boote et al., 1997; Heinemann et al., 2000; Mavromatis et al., 2001; Singh et al., 1999a, 1999b)

The purpose of this study was to evaluate the performance of RZWQM and DSSAT-CROPGRO-Soybean in predicting soybean yield and water use under a range of water availability conditions in the central Great Plains. If the models predict soybean water use, growth, and yield well, they will have application in evaluating the potential for soybean production in this region.

MATERIALS AND METHODS

Site Description

Studies were conducted during the 1985 and 1986 growing seasons at the USDA Central Great Plains Research Station, 6.4 km east of Akron, CO (40°9′ N, 103°9′ W; 1384 m above mean sea level). The soil type is a Rago silt loam (fine smectitic, mesic Pachic Argiustoll). Three experiments were conducted to provide a range of available water conditions in which to evaluate water stress effects on soybean productivity. The experiments varied in the method of water application and will be referred to as the line-source gradient irrigation experiment (LS), rainout shelter experiment (RO), and the drip irrigation experiment (Drip). Details of some cultural practices are given in Table 1, and irrigation and precipitation amounts are shown in Table 2. Growing season precipitation for this region ranges from 100 to 475 mm, averaging 245 mm. The precipitation plus irrigation amounts in the experiments generally fell within this range so that the experiments produced water availability conditions that would be experienced under a range of naturally occurring dryland conditions. Other details for each experiment are provided below. In all experiments, the soybean variety was 'Pioneer Brand 9291' (late group II).

Line-Source Gradient Irrigation Experiment

This experiment was conducted as a limited irrigation study, with irrigations applied from 23 June to 28 August in 1985 and from 26 June to 25 August in 1986. Most of the irrigations were applied in the last half of the growing season (flowering and grain filling). Irrigations were applied with a solid-set line-

Table 1. Cultural practices for soybean experiments, Akron, CO.

Experiment†	Year	Planting date	Harvest date	Row spacing	Plot dimensions	Population	Irrigation method
				m	m	plants ha^{-1}	
LS	1985	23 May	3 Oct.	0.76	4.1 × 12.2	375 600	Overhead impact sprinklers
LS	1986	20 May	25 Sept.	0.76	4.1 × 12.2	262 200	Overhead impact sprinklers
RO	1985	28 May	31 Sept.	0.53	2.7 × 2.7	331 100	Flood
RO	1986	20 May	25 Sept.	0.53	2.7 × 2.7	397 600	Flood
Drip	1986	20 May	25 Sept.	0.76	4.6 × 9.0	271 100	Drip

† LS, line-source gradient irrigation experiment; RO, rainout shelter experiment; Drip, drip irrigation experiment.

source gradient irrigation system, with full irrigation next to the irrigation line and linearly declining water application as distance increased away from the line. Details regarding the irrigation system can be found in Nielsen (1997). Four irrigation levels existed along the line-source system. These four levels were replicated twice in 1985 and four times in 1986. A soil water measurement site and irrigation catch gauge were located at the center of each plot. There were seven irrigations in 1985 and nine in 1986. Total irrigation amounts ranged from 3 to 129 mm in 1985 and from 16 to 250 mm in 1986.

Rainout Shelter and Drip-Irrigated Experiments

Details for these experiments are found in Nielsen (1990). Briefly, both experiments had four levels of irrigation determined by four threshold levels of the Crop Water Stress Index (Gardner et al., 1992), computed from crop canopy temperatures measured daily with an infrared thermometer. In both experiments, the irrigation treatments were laid out in a randomized complete block, with three replications in RO and five in Drip. Irrigations were flood-applied in RO. In the Drip plots, irrigations were applied through drip-irrigation tubing laid on the surface of every other interrow space. Total irrigation amounts ranged from 306 to 533 mm in 1985 (RO), 457 to 559 in 1986 (RO), and from 145 to 181 in 1986 (Drip).

Soil Water Measurements and Crop Water Use Calculation

Soil water measurements were made at planting and harvest and at several intermediate times during the growing seasons. These measurements were made at 15, 45, 75, 105, 135, and 165 cm below the soil surface with a neutron probe calibrated previously against soil water samples taken in the plot area and covering a range of water contents from 10 to 28 cm^3 cm^{-3}. Crop water use (ET) was calculated as the difference between successive soil water measurements plus precipitation and irrigation during the sampling period. Runoff and deep percolation were assumed to be negligible.

Leaf Area Index, Biomass, and Plant Height Measurements

Leaf area index, aboveground biomass, and plant height measurements were taken only during the 1985 growing season in the LS experiment. One meter of row was destructively sampled from each plot on four sampling dates, and leaf area was measured with a leaf area meter (LI-3100, LI-COR, Lincoln, NE).[1] Plant height (measured from the soil surface to the top of the plant canopy) was measured on eight dates in each plot of the LS experiment.

Table 2. Irrigation and rainfall amounts, Akron, CO.

Year	Experiment	Irrigation level 1	2	3	4	Rainfall
		mm	mm	mm	mm	mm
1985	Line-source gradient	3	34	89	129	212
1986	Line-source gradient	16	72	171	250	167
1985	Rainout Shelter	347	347	423	500	0
1986	Rainout Shelter	457	508	508	559	0
1986	Drip	145	174	180	181	167

Model Calibration

Calibrations of both RZWQM and CROPGRO-Soybean were done using the 1985 Irrigation Level 4 (wettest) data of the LS, as suggested by Boote (1999). The RZWQM was calibrated based on measured LAI, plant height, aboveground biomass, ET, and yield using parameters found to be important in studies conducted previously to test the model for soybean in Ohio (Landa et al., 1999), Missouri (Ghidey et al., 1999), and Iowa (Jaynes and Miller, 1999) as part of MSEA. The parameter values obtained from the calibration process were then used to predict soybean production at the other irrigation levels from the 1985 and 1986 LS as well as from the 1985 and 1986 RO and the 1986 Drip. Calibrated values obtained and used in the current study and default values and ranges of crop-related model parameters from the MSEA studies are listed in Table 3 and are incorporated into the RZWQM plant parameter database. The calibration process is an iterative, trial-and-error process described by Hanson (2000) and Hanson et al. (1999). In this particular study, our calibration strategy was to put emphasis on correct simulation of yield and ET, with due considerations of soil water content, LAI, biomass, plant height, and phenology. We changed the minimum leaf stomatal resistance from 200 to 100 s m^{-1} based on values measured in the Drip86 experiment (Nielsen, 1990). The maximum rooting depth was increased to 300 cm to increase root growth into the measured soil profile (0–180 cm) and improve estimates of water uptake from each soil layer compared with measured values without changing other model parameters. Increasing maximum rooting depth to 300 cm does not increase the actual depth of rooting allowed by the model (180 cm) but does increase the rate of root growth in various layers of the soil profile (Ahuja and Ma, 2002).

Soil hydraulic properties for use with RZWQM were estimated from soil texture and table values of Rawls et al. (1982) (Table 4). Water fitness (EWP) is calculated as the ratio of actual ET to potential ET. The effect of EWP (EEWP) on photosynthesis is scaled from 0 to 1 as EWP varies from 0.5 to 0.8. The net effect of water stress on photosynthesis is calculated as $1 - (1 - \text{EEWP})$ (Hanson, 2000). The RZWQM was run under a no-N-stress condition because N is not a limiting factor for inoculated soybean. The RZWQM was run using daily weather data (daily maximum and minimum temperatures; daily average humidity; and daily total rainfall, solar radiation, and wind run) recorded by an automated weather station operating approximately 500 m from the plot areas.

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[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA.

Table 3. Calibrated and default plant model parameters used in RZWQM for soybean grown at Akron, CO.

Parameter	Calibrated	Default values or ranges
Minimum leaf stomatal resistance, s m^{-1}†	100	200
Proportion of photosynthate to propagules during reproductive stage, dimensionless†	0.25	
Proportion of photosynthate lost to respiration, dimensionless†	0.17	0.005–0.1500
Photosynthesis rate at reproductive stage compared with vegetative stage	0.70	0.25–0.90
Photosynthesis rate at seedling stage compared with vegetative stage	0.70	0.30–0.70
Coefficient to convert leaf biomass to LAI‡ (CONVLA), g LAI^{-1}†	1.9	1.5–4.0
Plant population on which CONVLA is based (CLBASE), plants ha^{-1}†	370 137	22 500–23 000
Maximum rooting depth, cm†	300	100
Maximum plant height, cm	70	50
Aboveground biomass at one-half maximum height, g	4	4
Aboveground biomass of a mature plant, g	13	35
Minimum time needed for plant to germinate, d§	3	5
Minimum time needed for plant to emerge, d§	7	11–15
Minimum time needed for plant to grow to four-leaf stage, d§	22	22–29
Minimum time needed for plant to complete vegetative growth, d§	62	62–74
Minimum time needed for plant to complete reproductive growth, d§	92	92–119
Growth stage advanced from planting to germination, dimensionless	0.0356	0.0356
Growth stage advanced from planting to emergence, dimensionless	0.065	0.065
Growth stage advanced from planting to four-leaf stage, dimensionless	0.20	0.20
Growth stage advanced from planting to end of vegetative growth, dimensionless	0.75	0.75
Growth stage advanced from planting to physiological maturity, dimensionless	0.90	0.90

† Calibration parameters suggested by the model developers (Hanson et al., 1999; Hanson, 1999).
‡ LAI, leaf area index = leaf biomass per plant × plant population/(CONVLA × CLBASE).
§ Calendar days.

The CROPGRO-Soybean model was used as part of the DSSAT system. Parameters for this model were also calibrated with the 1985 LS data set at Irrigation Level 4 based on the DSSAT user's guide (Boote, 1999). The drained upper limit and drained lower limit (Table 4) were estimated through the wizard provided in the DSSAT 3.5 interface based on soil texture (Hunt et al., 1994). Calibrated cultivar parameters were based on maturity group II provided by the model and are shown in Table 5. For comparison, Table 5 also shows the standard default values used by CROPGRO-Soybean for maturity group II.

Both models were run from 1 January to 31 December. Initial soil matric potentials were assumed to be 0.033 MPa.

SIMULATION RESULTS AND DISCUSSION

Calibration Data Set

The RZWQM and CROPGRO-Soybean simulated the correct trends of LAI, plant height, and aboveground biomass, as shown in Fig. 1. The RZWQM predicted a slightly greater maximum LAI than did CROPGRO-Soybean. Because we did not collect LAI data during the period of LAI decline, we are unable to evaluate which model better predicted the rate of leaf senescence. Both models overpredicted plant height during the middle of the growing season. Biomass fol-

Table 4. Measured soil texture and estimated hydraulic properties for Rago silt loam, Akron, CO.

Soil depth	Bulk density	Sand	Silt	Clay	Drainage limit† Upper	Drainage limit† Lower	Saturated hydraulic conductivity‡
cm	g cm^{-3}	%	%	%	cm^3 cm^{-3}	cm^3 cm^{-3}	cm h^{-1}
0–30	1.33	39.0	41.7	19.3	0.260	0.131	1.32
30–60	1.33	32.3	44.3	23.4	0.263	0.135	1.32
60–90	1.36	37.0	40.7	22.3	0.241	0.114	1.32
90–120	1.40	45.7	36.7	17.6	0.219	0.089	1.32
120–150	1.42	45.7	42.3	12.0	0.209	0.081	1.32
150–180	1.42	48.0	41.7	10.3	0.209	0.081	1.32

† The upper and lower drainage limits used in CROPGRO were generated by the DSSAT soil data wizard using measured values of sand, silt, clay, bulk density, pH, and organic matter.
‡ Estimated from Rawls et al. (1982).

Table 5. Cultivar traits (calibrated and standard default values for maturity group II soybean) used in CROPGRO-Soybean.

Parameter	Calibrated	Default
Critical daylength for crop development, h	13.59	13.59
Sensitivity to photoperiod, 1/h	0.249	0.249
Time from end of juvenile phase to first flower, photothermal days	20	17.4
Time from first flower to first pod greater than 0.5 cm, photothermal days	6	6
Time from first flower to first seed, photothermal days	13.5	13.5
Time from first seed to physiological maturity, photothermal days	20	33
Time from first flower to end of leaf growth, photothermal days	26	26
Maximum leaf photosynthesis rate, μmol CO$_2$ m^{-2} s^{-1}	1.0	1.03
Specific leaf area, cm^2 g^{-1}	250	375
Maximum size of fully expanded leaf, cm^2	180	180
Maximum fraction of daily available photosynthate to seeds plus shells, dimensionless	1.0	1.0
Maximum weight per seed, g	0.19	0.19
Seed filling duration for a cohort of seed, photothermal days	20	23
Average seeds per pod	2.2	2.2
Time for cultivar to add full pod load under optimal conditions, photothermal days	8.0	10.0

lowed the course of measured data well, with CROPGRO-Soybean predicting an end-of-season decline in biomass. Simulated soybean seed yield by RZWQM was 2696 kg ha^{-1} compared with the measured yield of 2678 kg ha^{-1}, a 0.7% overestimation. Yield from CROPGRO-Soybean was 2617 kg ha^{-1}, a 2.2% underestimation. Simulated ET from 9 July to 24 Sept. 1985 was 38.8 cm from RZWQM compared with a measured ET of 40.5 cm (with standard error of 0.7 cm), which represents a 4% underprediction. Simulated ET from CROPGRO-Soybean was 32.2 cm, a 20% underprediction.

Although plant phenology was not the focus of RZWQM, the model did simulate the initiation and end of reproductive stages (data not shown). We observed that soybean reached R3 stage (beginning pod) (Fehr and Caviness, 1977) on 1 Aug. 1985. From previous field experience, we estimated that reproductive stage (R1) was initiated around 19 July 1985. The RZWQM simulated a later initiation of reproductive development, with 33% of the plant population in reproductive stage on 4 August. The model also simulated 91% of plants reaching maturity on 16 Sept. 1985 at field-observed R8 stage (full maturity). Soybean leaf number and reproductive growth stage were estimated very well by CROPGRO-Soybean for the calibration data set (Fig. 2).

Water contents in the soil profile (Fig. 3) were generally simulated by RZWQM and CROPGRO-Soybean correctly, predicting the decline in soil water at depths below 30 cm that occurs with plant growth and root development. Both models also correctly simulated the increases and decreases in surface-layer (0–30 cm) soil water content that occurred with periods of rainfall followed by drying. The RZWQM tended to overpredict soil water contents in the 60- to 90-cm soil profile later in the growing season. With measured soil water content

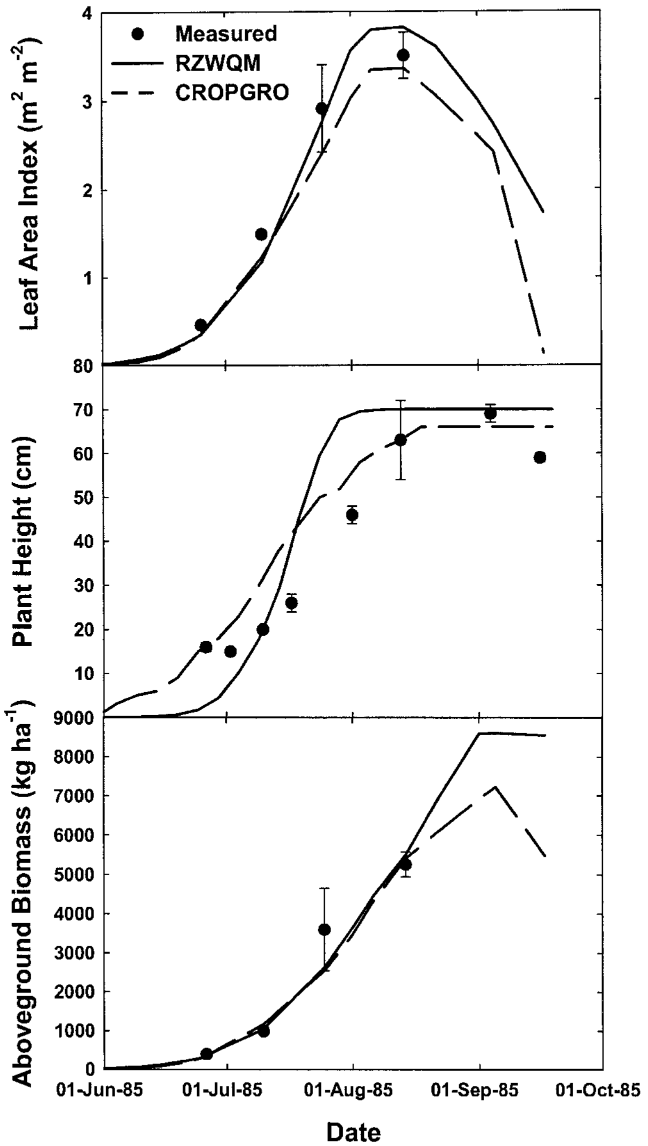

Fig. 1. Measured and simulated leaf area index, plant height, and aboveground biomass from Irrigation Level 4 (wettest) of the 1985 line-source gradient irrigation data set (used to calibrate RZWQM and CROPGRO-Soybean for soybean production in northeast Colorado). Bars are ± one standard deviation.

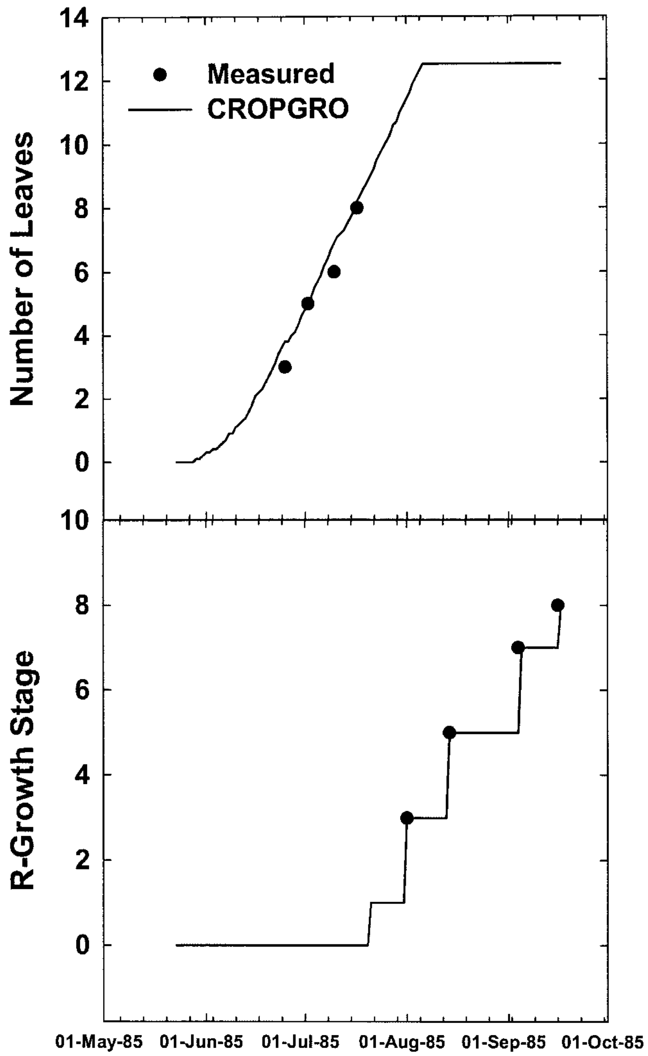

Fig. 2. Measured and simulated (CROPGRO-Soybean) leaf number and R-stages for the calibration data set (1985 line-source gradient irrigation experiment, Irrigation Level 4), Akron, CO.

at 33 kPa suction and saturated hydraulic conductivities calibrated for each soil layer based on surface runoff, Ghidey et al. (1999) reported that volumetric water content under soybean in Missouri was underestimated by RZWQM at all soil depths below 15 cm. The soil types in this study were silt loams in the surface and silty clay loams in the subsurface horizons. On the other hand, Jaynes and Miller (1999) reported small overestimations by RZWQM of soil water at all soil depths for soybean in Iowa on a well-drained loam soil. Wu et al. (1999) found that RZWQM estimated soil water under soybean on a highly permeable fine sand in Minnesota fairly well at 15 cm but overestimated soil water deeper in the profile, leading to fairly large overestimates of total water depth in the 150-cm profile. In the present study, CROPGRO-Soybean underpredicted soil water content at 0- to 30-cm soil profile later in the growing season and at 30- to 60-cm soil profile at all sampling dates. CROPGRO-Soybean also predicted water contents in the 60- to 90-cm and 90- to 120-cm layers very well. Most of the measured water extraction below 120 cm, correctly predicted by RZWQM, was missed by the CROPGRO-Soybean simulation. As shown for the calibration data set in Fig. 4, RZWQM underestimated water extraction by about 4.3 cm during the first half of the growing season and overestimated water extraction by about 3.6 cm during the second half of the growing season. Consequently, for the entire growing season, RZWQM came very close to predicting the correct ET (Fig. 5). CROPGRO-Soybean similarly underestimated first-half ET by 4.6 cm but only underestimated second-half ET by 0.5 cm, resulting in an underestimate of ET for the entire growing season.

For the calibration data set, both models performed equally well in simulating LAI, biomass, plant height, and soybean yield. However, RZWQM estimated ET better than CROPGRO-soybean because RZWQM provided somewhat better simulation of soil water contents and soil water extraction, particularly in the lower soil depths (Fig. 3). CROPGRO-Soybean determines rooting depth and distribution from the Soil Root Growth Factor (SRGF), formerly called the Root Weighting Factor (Ritchie, 1998). The original values of SRGF that we used (0.86, 0.64, 0.41, 0.22, 0.12, 0.07, and 0.04) were increased to 1.00, 0.50, 0.50, 0.50, 0.35, 0.35, and 0.20 for the 0- to 15-, 15- to 30-, 30- to 60-, 60- to 90-, 90- to 120-, 120- to 150-, and 150- to 180-cm depths, respectively. This resulted in only minor increases in yield and ET.

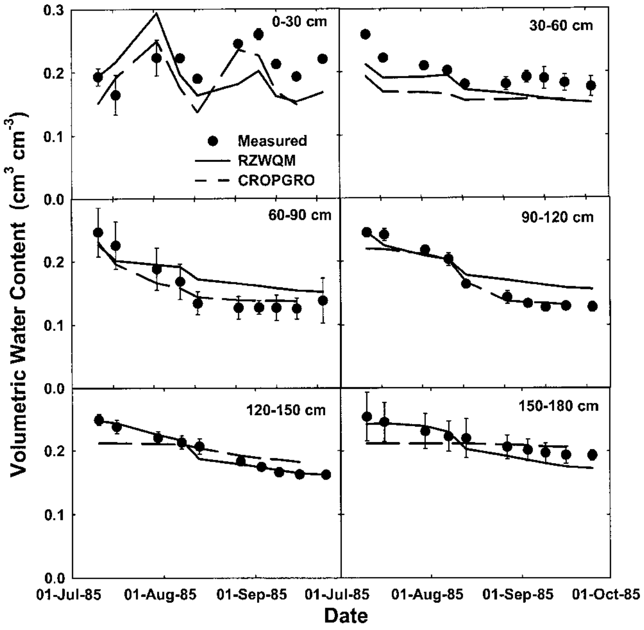

Fig. 3. Measured and simulated volumetric soil water content by soil layer from Irrigation Level 4 of the 1985 line-source irrigation data set with soybean at Akron, CO.

Model Evaluation

The RZWQM simulated ET fairly well for the LS85 and Drip86 experiments (Fig. 5). For the LS86, RO85, and RO86 experiments, RZWQM overestimated ET fairly consistently by about 7 to 10 cm. For all five experiments, the model did pick up the relative increases in ET with increased irrigation application. On the other hand, CROPGRO-Soybean did not simulate the ET increase with increased water application for the RO85 and RO86 experiments as well as RZWQM. The LS86 ET data were overpredicted by CROPGRO-Soybean by about the same amounts as RZWQM overpredicted ET for that data set, but CROPGRO-Soybean underpredicted the LS85 and Drip86 ET by greater amounts than RZWQM. For both the RO85 and RO86 experiments, CROPGRO-Soybean simulated about 40 cm of ET, regardless of irrigation level. The ET for the highest irrigation level of the LS86 experiment also seems to be capped at 40 cm. A possible explanation may be that large amounts of drainage were simulated by CROPGRO-Soybean [8–19 cm for the various irrigation levels in the RO85 and RO86 experiments (data not shown)]. The RZWQM did not predict drainage for any of the experiments. Drainage for both models is defined as water that leaves the 180-cm soil depth. We increased the values for the drained upper limit in CROPGRO-Soybean to 0.398, 0.398, 0.411, 0.366, 0.341, 0.329, and 0.356 for the 0- to 15-, 15- to 30-, 30- to 60-, 60- to 90-, 90- to 120-, 120- to 150-, and 150- to 180-cm layers, respectively. After making this change, predicted drainage from CROPGRO-Soybean was reduced, ranging from 0 to 14 cm for the various irrigation levels in the RO85 and RO86 experiments. This change increased ET estimates 5 to 6%, but the CROPGRO-Soybean predictions of ET still showed no effect of increasing irrigation amount.

The total amount of water extracted from the 180-cm soil profile (Fig. 4) was not simulated well by RZWQM during the first half of the growing season (before 1 August) for the LS86 and Drip86 experiments (note: a negative water extraction value means soil water increased during the measurement interval). The RZWQM overestimated soil water extraction for these eight points by 3.5 to 9.7 cm. Results during this same period were somewhat similar from CROPGRO-Soybean. During the second half of the growing season, RZWQM underpredicted water extraction for the Drip86 experiment

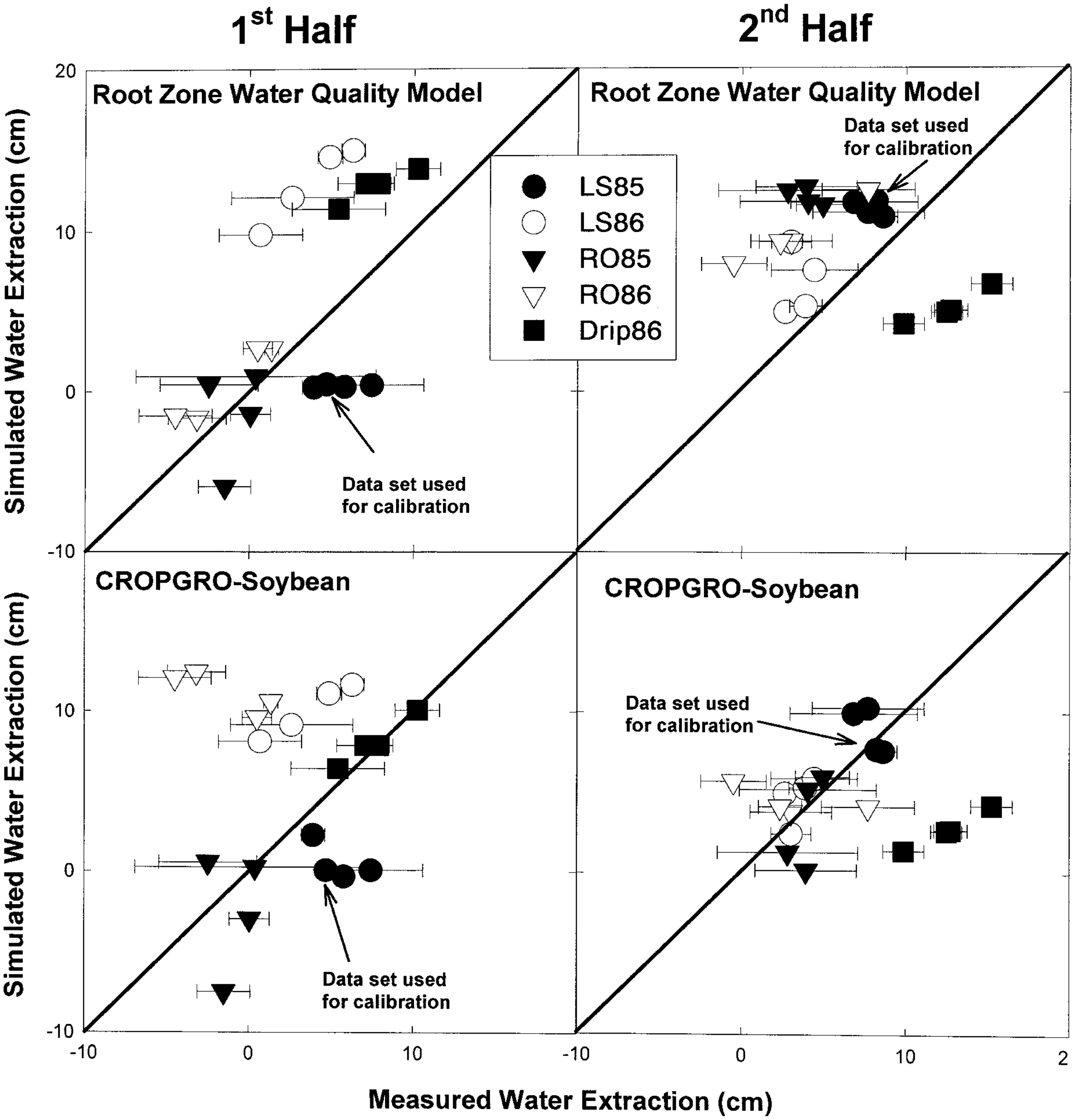

Fig. 4. Measured vs. simulated soil water extraction from the 0- to 180-cm soil profile by soybean at Akron, CO (first half of growing season is before 1 August). Bold diagonal line is 1:1 line. LS, line-source gradient irrigation experiment; RO, rainout shelter experiment; Drip, drip irrigation experiment.

and overpredicted water extraction for the other experiments. CROPGRO-Soybean also underpredicted water extraction during the second half of the growing season for the Drip86 experiment. The other data sets had water extraction simulated fairly closely by CROPGRO-Soybean. Over all data sets, CROPGRO-Soybean simulated water extraction more closely than RZWQM (root mean square difference of 6.2 cm for RZWQM and 5.0 cm for CROPGRO-Soybean). We do not have an explanation for why both models underpredicted soil water extraction by about the same amount for the Drip86 experiment.

Farahani et al. (1999) also reported underestimation of soil water extraction for the 0- to 150-cm profile by RZWQM during the second half of the growing season for 1 yr of dryland corn data in northeast Colorado. One year of soybean data from the 150-cm soil profile in Minnesota showed overestimation of soil water extraction in the first half of the growing season and underestimation of soil water extraction in the second half (Wu et al., 1999).

For LAI data collected from 25 June to 14 Aug. 1985 in the LS, no significant differences were found among the four irrigation levels, which was correctly predicted with RZWQM (data not shown). However, CROPGRO-Soybean predicted a decrease in LAI with water stress during that experimental period. As stated earlier, the LS85 data set had most of its irrigations applied during the last half of the growing season. The first irrigation was applied on 23 June 1985 (4.2 cm for the

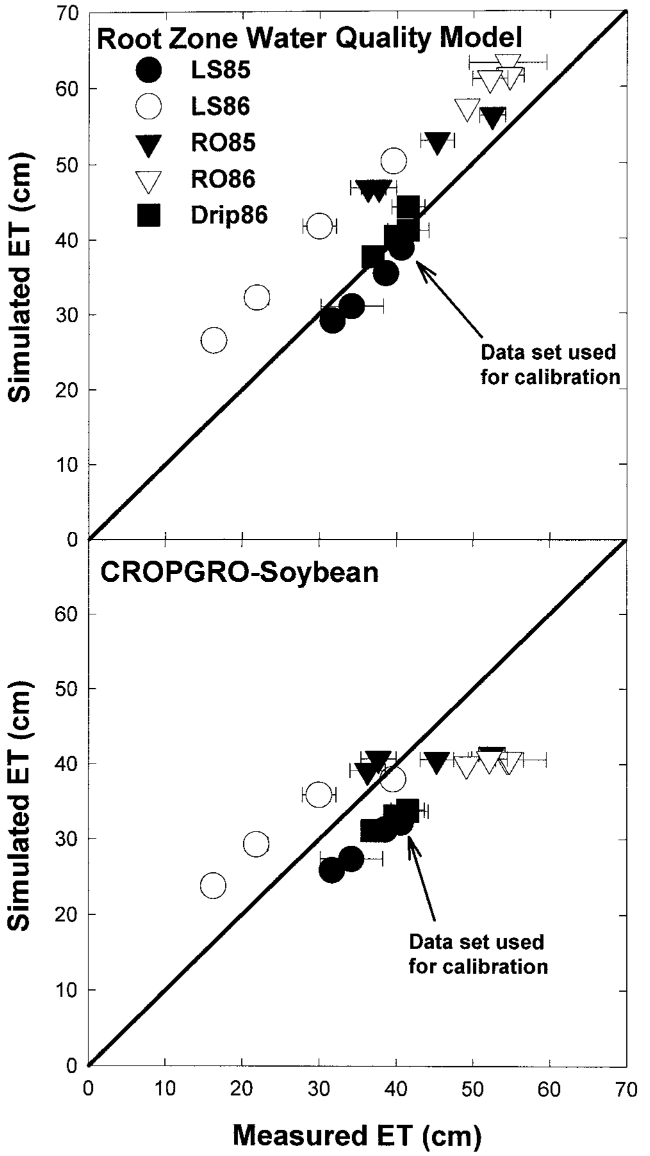

Fig. 5. Measured vs. simulated soybean evapotranspiration (ET), Akron, CO. Bold diagonal line is 1:1 line. LS, line-source gradient irrigation experiment; RO, rainout shelter experiment; Drip, drip irrigation experiment.

high irrigation level). Then no irrigations were applied until 21 Aug. 1985 [well into the reproductive phase, stage R5 (beginning seed)]. We would not expect these late irrigations to result in significant leaf area differences. We would expect them to have a large effect on pod filling and seed size. Even with similar LAI, treatments with different amounts of irrigation and available water would have differences in ET due to differences in plant water status and stomatal opening. Those ET differences were measured and correctly modeled by RZWQM in 1985 (Fig. 5). Both models adequately predicted plant canopy height for 1985 but underpredicted canopy height for 1986 (data not shown). Maximum canopy height was overpredicted by 30 to 100% by both models, suggesting that the models failed to account for drought effects on plant height in 1986 after model calibration in the relatively wet year of 1985.

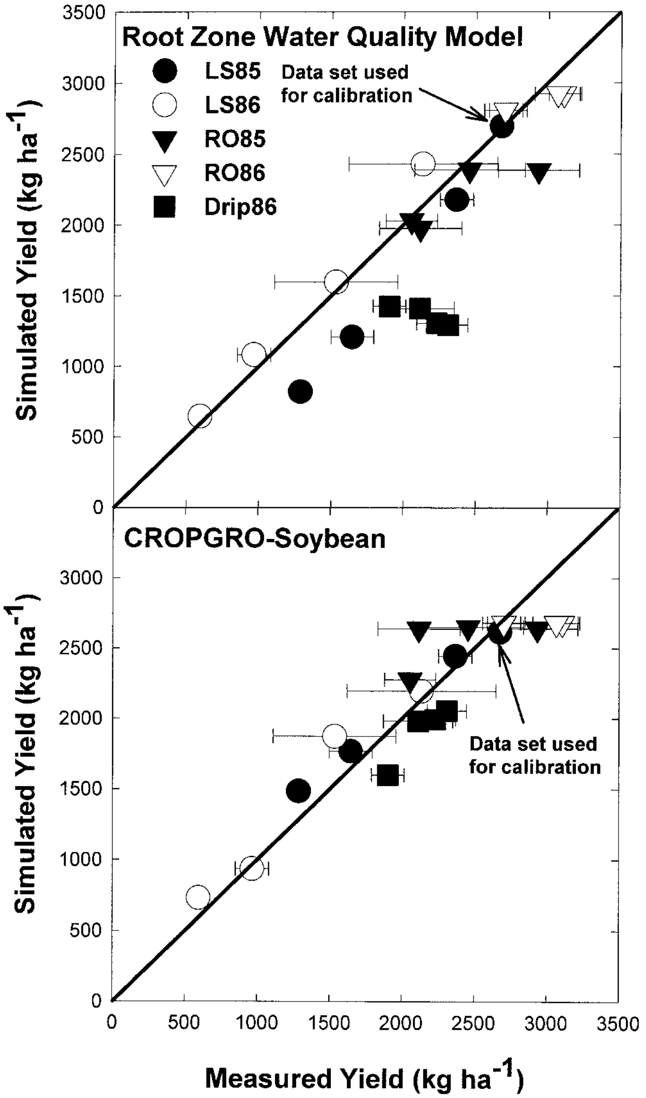

Fig. 6. Measured vs. simulated soybean yield, Akron, CO. Bold diagonal line is 1:1 line. LS, line-source gradient irrigation experiment; RO, rainout shelter experiment; Drip, drip irrigation experiment.

In general, RZWQM was able to show yield increases that followed the yield increases measured in the field in response to increased water availability (Fig. 6). But only 11 of the 19 data sets evaluated (not counting the calibration data set) had RZWQM yield estimates within 10% of measured values. The RZWQM more frequently underpredicted soybean yield than overpredicted. CROPGRO-Soybean did a better job of simulating yield than did RZWQM (root mean square difference of 246 kg ha^{-1} for CROPGRO-Soybean and 423 kg ha^{-1} for RZWQM). Compared with RZWQM simulations, CROPGRO especially did a better job of yield estimation in Drip. However, CROPGRO-Soybean yields appeared to be insensitive to irrigation amounts in the two ROs.

The yield insensitivity of CROPGRO-Soybean to increased irrigation noted in the RO85 and RO86 experiments may be related to the ET insensitivity discussed earlier in these two experiments. For soil water redistribution during infiltration, water is moved downward

Table 6. Seasonal sums of daily water stress parameters from RZWQM (1 − EWP†), CROPGRO-Soybean (WSGD‡), and canopy temperature measurements (CWSI§).

Irrig.	LS85¶			LS86			RO85#			RO86			Drip86††		
level	1 − EWP	WSGD	CWSI	1 − EWP	WSGD	CWSI	1 − EWP	WSGD	CWSI	1 − EWP	WSGD	CWSI	1 − EWP	WSGD	CWSI
1	21.2	18.0	NA‡‡	31.5	32.2	NA	11.5	0.0	11.6	8.2	0.6	10.4	17.9	13.5	9.8
2	17.9	15.9	NA	26.4	25.0	NA	11.8	0.0	9.5	1.5	0.6	8.9	15.5	8.6	7.3
3	13.0	9.4	NA	18.3	11.6	NA	2.4	0.0	8.4	1.8	0.6	5.1	15.1	8.4	5.1
4	9.3	4.3	NA	8.3	4.7	NA	0.0	0.0	4.9	0.1	0.6	5.3	15.2	7.8	4.3

† EWP, water fitness parameter from RZWQM.
‡ WSGD, water stress for growth parameter from CROPGRO-Soybean.
§ CWSI, Crop Water Stress Index from infrared thermometer canopy temperature measurements.
¶ LS, line-source gradient irrigation experiment.
# RO, rainout shelter experiment.
†† Drip, drip irrigation experiment.
‡‡ NA, not available.

from the top soil layer to lower layers in a cascading (tipping bucket) approach. Drainage from a layer takes place only when the soil water content is between field saturation and the drained upper limit (Ritchie, 1998). Perhaps for these simulations, we have inaccurately defined the drained upper limit. As stated earlier, CROPGRO-Soybean predicted large amounts of drainage for the ROs (8.3–13.6 cm in 1985 and 11.5–19.4 cm in 1986). Consequently, the soil water profile was never far from field capacity. Photosynthesis and transpiration are reduced in direct proportion to the ratio of potential water uptake to potential transpiration. With a predicted soil water profile always near field capacity, there would be little reduction in potential water uptake and little effect on photosynthesis, transpiration, and yield.

As stated earlier, increasing the drained upper limit values from those given in Table 4 decreased drainage amounts, increased ET by 5 to 6%, and increased yield by less than 1% for all four levels of the RO86 data set. So incorrect specification of the drained upper limit does not seem to be the problem relative to the lack of yield response by CROPGRO-Soybean to decreasing water availability in the RO85 and RO86 data sets.

Analysis of the calibration data set with the original rooting function showed that CROPGRO-Soybean put relatively more of its roots in the 0- to 30-cm layer (≈62 vs. 42%) than did RZWQM (data not shown). Both models had about the same amount of roots in the 30- to 60-cm layer. The RZWQM had a higher percentage of its roots in the 60- to 90- and 90- to 120-cm layers than CROPGRO-Soybean. Both models had very few roots below 120 cm (7% for RZWQM, 1% for CROPGRO-Soybean). Use of the more aggressive rooting function as mentioned earlier did not make CROPGRO-Soybean predictions of ET and yield responsive to decreasing water availability in the RO85 and RO86 data sets.

Table 6 shows that CROPGRO-Soybean predicted no growth-reducing water stress for any irrigation level in the RO85 experiment and only an insignificant amount that did not vary with irrigation level in the RO86 experiment. On the other hand, RZWQM did predict higher water stress with decreased irrigation in those two experiments. This matched the field-observed water stress quantified with the Crop Water Stress Index computed from measurements of canopy temperature (Nielsen, 1990). Consequently, RZWQM predicted small reductions in yield with decreased water application while CROPGRO-Soybean did not. In the other three experiments, when water stress parameters indicated that water stress was being simulated by CROPGRO-Soybean, the yields appear to be reduced appropriately as water availability declines. Similarly, RZWQM simulated water stress correctly for the LS85 and LS86 experiments, with corresponding decreases in yield as water availability declined. We are without an explanation for the lack of water stress and yield response to irrigation treatment by RZWQM for the Drip86 data set and by CROPGRO-Soybean for the RO85 and RO86 data sets.

In summary, RZWQM and CROPGRO-Soybean were evaluated for their ability to simulate soybean growth, development, water use, and yield under a range of water availability conditions in the central Great Plains. Model estimates were generally close to measured values for both models although RZWQM provided closer ET estimation and CROPGRO-Soybean better simulated crop yield. Both models should be useful tools for evaluating the potential of soybean as an alternative crop in dryland rotations in the central Great Plains. A hybrid of RZWQM and CROPGRO-Soybean may further improve simulation results.

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