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Site-specific evaluation of the CROPGRO-soybean model on Missouri claypan soils

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Abstract

Crop yield is affected by many factors, primarily encompassing soil and weather conditions, and crop management practices. Crop modeling can be used to help understand how multiple factors interact and impact yield. The CROPGRO modeling package has been used extensively to assess the effects of management practices and environmental conditions on soybean growth and development. However, the model has not been thoroughly evaluated for some environments that have unique characteristics such as claypan soils in which the depth to the claypan horizon can vary greatly within fields. The objectives of this study were to evaluate the performance of the CROPGRO-Soybean model for simulating site-specific crop growth, soil water content, and grain yield on claypan soils. Data were obtained during low and average rainfall conditions from two sites over 3 years in central Missouri. Plant (e.g. yield, leaf area, root length density) and soil (e.g. topsoil thickness, moisture, texture) measurements were collected for calibrating and validating the model. Results indicated that CROPGRO-simulated soil water contents in the 15–90 cm soil profile agreed well with measured values. Simulated leaf area index and grain yield also agreed well with measured values during average precipitation years, but were under-estimated during extremely dry years. Within-season precipitation and claypan soil topsoil depth were shown to have greatest influence on soybean yield. Although we hypothesized it to be otherwise, field measurements in 1997 showed that the claypan did not negatively affect soybean root penetration.
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Keywords: CROPGRO; Soybeans; LAI; Root distribution; Soil water content

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1. Introduction

Crop yield is influenced by management practices, soil and weather conditions. The main functions of soil are to provide mechanical support for the plant and to supply nutrients, water, and oxygen required by the plant. Generally, reduction in the productive capacity of the soil may be attributed to conditions when one or more of these soil factors are suboptimal and cause plant growth stress. Soil properties, such as soil texture, thickness of the A horizon, organic matter content, soil pH, cation exchange capacity, bulk density, and soil profile wetness vary with landscape position (Brubaker et al., 1993; Mulla et al., 1992) and as such can cause spatial variation in crop yield.

Crop production variation is a function not only of spatially-variable landscape/soil factors, but also of temporally-variable climate factors. Climate interacts with soil and landscape resulting in a dynamic environment for plant growth. Sometimes year-to-year climate variability may have more impact on yield than spatial variability. Spatial variability can have negligible effects on crop yield in some years (Mulla and Schepers, 1997). On the other hand, high-producing areas of a field during "dry" years can be low-producing areas of the same field in "wet" years (Colvin et al., 1997; Sudduth et al., 1997). Improving our understanding of the interactive effects of management practices and soil and weather conditions, can enhance yield, improve the use efficiency of natural resources, and reduce the potential for environmental pollution.

Variable-rate application of crop inputs (e.g. fertilizer, irrigation, pesticide, and herbicide) is commonly used in some locations. A potential failing of this site-specific management is that the decision rules are usually generalized recommendations. Knowledge of the relationships between soil properties, weather, and management practices and crop yield is needed in a wide range of situations in order to pre-test management options being considered.

Crop modeling is a technology that has been applied in precision farming, farm planning, and policy development. Crop models effectively integrate numerous factors affecting crop environment and yield (Tsuji et al., 1994). They not only can be used to predict yield but also can be used to evaluate the variability and risks of different management strategies over a range of locations and climatic conditions (Tsuji et al., 1994). Crop modeling can help decision makers reduce the time and human resources required for developing alternative and/or optimal management strategies.

The Decision Support System for Agrotechnology Transfer (DSSAT) is a suite of crop models integrated into a single software package in order to facilitate the application of crop simulation in research and decision-making. These models share a common input and output file format. The DSSAT package is specifically designed to answer "what if" questions frequently asked by policy makers and farmers concerned with sustaining an economically and environmentally safe agriculture (Tsuji et al., 1994). Recently, the DSSAT crop models, such as CERES and CROPGRO have been extensively validated and applied in various research areas and production environments. Examples include optimizing irrigation (Heinemann et al., 1999),

evaluating nitrogen balance and the effects of soil water excess under different conditions (Asare et al., 1996; Garrison et al., 1999; Kizaso and Ritchie, 1997), determining chemical leaching potential (Pang et al., 1998), testing for cultivar performance (Irmak et al., 1999; Piper et al., 1998), and predicting crop development and seed yield (Batchelor et al., 1994; Sau et al., 1999; Alagarswamy et al., 2000).

CROPGRO is a process-oriented model for grain legumes, based on the SOYGRO, PNUTGRO, and BEANGRO models, that considers crop carbon, soil water, and soil nitrogen balance. Although the ability of the CROPGRO-Soybean model to simulate observed soil water content and soybean yields in different regions has been established (Uehara and Tsuji, 1998), the model is quite complex and requires many model input parameters to be determined. After calibrating and validating for a specific environment, the model can be used to assess alternative management choices.

One unique crop production environment for which model calibration is needed is the claypan soil region. Claypan soils (Vertic Epiaqualfs and Vertic Albaqualfs) occupy about 4 million ha in Missouri and Illinois. These soils are characterized by a restrictive clay layer ("claypan") which limits downward water flow and drainage (Jamison et al., 1968). The soils thus have a unique hydrology and productivity relationship.

The objectives of this research were: (1) to evaluate the CROPGRO-Soybean model for its ability to simulate soil water content, soybean development, and grain yield for claypan soils in Missouri, (2) to investigate the distribution of soybean roots in the claypan soil profile, and (3) to investigate the influence of variable soil and weather conditions on soybean grain yield.

2. Materials and methods

2.1. Crop model

CROPGRO version v3.5 was used in this study. The main time step in CROPGRO is one day, corresponding to the daily weather information, but it computes canopy photosynthesis in hourly time steps using leaf-level photosynthesis parameters and hedge-row light interception calculations (Boote et al., 1998). A daily soil water balance is computed based on rainfall, runoff, drainage, and root water uptake. Model daily outputs include crop growth, water, nitrogen and carbon balance (Jones et al., 1994). In this study nitrogen balance was not simulated.

2.2. Site and experiment description

The two non-irrigated claypan soil fields (Field A which was 36 ha and Field B which was 28 ha) used for this study were located near Centralia, Boone County, in central Missouri (39.211 N, 92.162 W). Both were managed in a corn (*Zea mays* L.) and soybean (*Glycine max*. [L] Merr) rotation. Data were collected in 1997 and 1999

for Field B and in 1998 for Field A. No fertilizer was applied during soybean crop years. Herbicide and pesticide were applied uniformly over the entire field as needed. Additional management information is shown in Table 1.

The accumulated rainfall during the soybean growing season (1 May to 30 September) was 428 mm in 1997, 628 mm in 1998, and 299 mm in 1999. The 59-year mean rainfall for the same 5 months was 507 mm. For the purpose of this study, we defined a year with growing season precipitation between ±25% of the 59-year mean as a normal precipitation year. Thus, 1997 and 1998 were considered to be "normal" precipitation years, while 1999 was designated as a "dry" year.

Within-field monitoring sites were selected to represent the range in variability observed in existing soil and landscape parameters and yield maps measured by combine yield monitoring from 1993 to 1996. Topsoil depth (depth to the Bt horizon) and topographic attributes are among field features affecting water storage and flow within the field that directly affect yield. Therefore, these parameters were given special consideration when selecting monitoring sites. Six monitoring sites were selected for Field A and five sites for Field B. Site elevation, topsoil depth, slope and aspect of these sites are listed in Table 2.

2.3. Data collection

2.3.1. Soil parameters

Soil samples were collected with a hydraulic core sampler on 4 March, 1999. Cores were cut into subsamples by horizon and used for bulk density and soil textural composition determinations. The core method was used to measure bulk density and soil texture was analyzed using the pipet method (Gee, 1986). The drained lower and upper limits were estimated using the Brakesiek/Rawls LEACHW model available in SOILPAR (Soil Parameter Estimator) v1.0. SOILPAR (Donatelli et al., 1996) is computer software that includes several pedotransfer functions commonly used for estimating soil hydraulic parameters based on textural composition, bulk density and organic carbon content for the various soil layers. Saturated hydraulic conductivity (SSKS) was estimated based on the research conducted by Canqui (1995). The other soil physical and chemical properties required by the model were obtained

Table 1
Management information

	1997	1998	1999
Field	Field B	Field A	Field B
Cultivar	Dekalb CX 420 RR	S46–44 RM	Dekalb CX 390 RR
Cultivar type	Early GROUP IV	Mid-GROUP IV	Late GROUP III
Planting date	05/14/1997	05/28/1998	05/26/1999
Planting population (seeds/m^2)	47	49	54
Harvest date	10/18/1997	09/30/1998	09/30/1999
Harvest area (m^2)	10	25	27

Table 2
Monitoring site characteristics

Location	Site	Elevation (m)	Topsoil depth (cm)	Slope (%)	Aspect (degrees)
Field A	A1	263.1	25	1.25	67
	A2	263.6	44	0.37	315
	A3	263.5	36	0.26	12
	A4	263.3	15	0.56	87
	A5	264.4	41	0.32	12
	A6	264.9	32	0.10	304
Field B	B1	263.3	34	0.40	256
	B2	262.4	8	0.83	333
	B3	261.4	120	0.24	67
	B4	262.9	46	0.54	315
	B5	263.9	43	0.39	272

from a USDA-NRCS first order soil survey conducted on Field A in 1993. The range of soil parameters for study locations by horizons is summarized in Table 3.

2.3.2. Weather and soil water content

Daily weather data were collected from a weather station adjacent to Field A. Soil water contents were obtained by neutron probe measurements made every 7–10 days for Field B in 1997 and 1999, and by using a soil auger to sample for gravimetric soil moisture for Field A in 1998 (five times). The center depths of the measurements were 2.5, 10.0, 22.5, 37.5, 52.5, 75.0, and 105.0 cm.

2.3.3. Plant measurements

At each monitoring site, three random samples consisting of a 1-m row of plants were collected approximately every 3 weeks giving 6, 5, and 7 sampling times for 1997–1999, respectively. Leaf area was determined using a LI-COR leaf area meter (LI-3100), in which the projected image of a leaf sample traveling under a fluorescent light source is reflected by a system of mirrors to a solid-state scanning camera. Measurement error with this type of area meter is generally less than 2% (Hatfield et al., 1976). Yield measurements were obtained by hand harvesting sampling areas around the monitoring sites. Harvest dates and areas are shown in Table 1.

The root growth factor (SRGF) is a very important parameter in CROPGRO. It determines the ability of roots to grow and proliferate in a soil layer, which in turn affects the amount of soil water which can be taken up by roots. The root length density was measured to estimate SRGF for claypan soil instead of using assumed values for uniform, deep and well-drained soils. Measurement of root length density in the soil profile is difficult and time-consuming, and was limited to one site-year for this study, Field B in 1997. Three randomly placed cores (5.5 cm diameter, 120 cm long) were obtained within 1m of each monitoring site on 4 November 1997. Soil

Table 3
Ranges of soil parameters for study locations by horizon

Location	Soil horizon	Drained lower limit (cm^3/cm^3)	Drained upper limit (cm^3/cm^3)	Saturation (cm^3/cm^3)	Root growth factor	Sat. hyd. conductivity (cm/h)	Bulk density (g/cm^3)	Organic carbon (%)	Clay content (%)	Silt content (%)
Field A	Ap	0.13–0.19	0.34–0.42	0.39–0.45	0.82–1.00	3.12–7.14	1.38–1.56	1.17–1.18	15.8–28.8	63.9–77.9
	Ap/E	0.17–0.20	0.39–0.40	0.42–0.43	0.64	0.05	1.41–1.48	1.18	18.8–20.8	72.9–73.8
	E	0.20–0.25	0.41–0.47	0.45–0.49	0.47–0.64	0.001–0.05	1.37–1.44	0.39	31.3–39.0	54.5–59.7
	BE	0.23	0.40	0.45	0.34	0.05	1.39	0.67	35.9	57.5
	Bt1	0.29–0.38	0.45–0.55	0.50–0.56	0.32–0.66	0.001–0.05	1.19–1.35	0.83–1.10	53.4–67.3	31.8–46.2
	Bt2	0.20–0.30	0.41–0.49	0.45–0.53	0.14–0.48	0.001	1.30–1.57	0.83–0.96	31.3–55.7	44.0–65.7
	Btg1	0.21–0.25	0.35–0.46	0.45–0.48	0.11–0.19	0.001–0.01	1.29–1.48	0.38	32.6–46.9	51.1–66.4
	Btg2	0.20–0.24	0.33–0.44	0.43–0.47	0.08–0.35	0.001–0.01	1.29–1.53	0.15–0.24	34.4–42.7	56.8–65.4
	BCg	0.17–0.23	0.33–0.41	0.44–0.45	0.05–0.14	0.01	1.40–1.48	0.14–0.15	25.9–33.7	59.3–67.1
Field B	Ap	0.15–0.23	0.36–0.40	0.43–0.46	0.50–1.00	0.70–7.14	1.18–1.48	1.18	16.0–35.3	60.1–83.5
	A	0.19	0.39	0.45	0.47	0.70	1.39	0.97	18.8	79.1
	Ab	0.21	0.39–0.40	0.45–0.46	0.26–0.35	0.001	1.39–1.41	0.83	23.0–24.4	67.2–71.4
	AE	0.17–0.29	0.38–0.45	0.46–0.49	0.14–0.35	0.001–0.05	1.25–1.44	0.38–0.96	24.7–57.0	39.5–67.0
	BE	0.22–0.25	0.40–0.41	0.48	0.11–0.47	0.001–0.05	1.45–1.48	0.38–1.18	26.9–33.7	59.3–63.6
	Bt1	0.25–0.33	0.45–0.48	0.48–0.52	0.32–0.85	0.001–0.37	1.27–1.41	0.67–1.18	41.1–61.7	37.5–55.1
	Bt2	0.25–0.31	0.43–0.47	0.47–0.51	0.29–0.85	0.001	1.30–1.50	0.67–0.96	36.8–54.7	42.4–60.3
	BC	0.23–0.28	0.40–0.44	0.43–0.47	0.07–0.56	0.001–0.01	1.35–1.55	0.38–0.96	33.7–46.9	51.1–61.3
	C	0.20	0.40	0.43	0.07–0.08	0.01	1.45	0.15	33.7–39.1	59.3–60.3

samples were cut into 7.5 cm subsamples for the first 30 cm, 15.0-cm subsamples from 30 to 90 cm, and 30-cm subsamples below 90 cm. Soil roots were separated from soil by using water, air, and 930-μm mesh screens in a hydropneumatic elutriation system (Smucker et al., 1982). Debris was removed manually, and the roots were stored in sealed plastic bags at 3 °C. Roots were stained dark blue by placing them for 5 min in a heated (50 °C) crystal violet solution (1 g crystal violet stain/100 ml H_2O), and then returned to cool storage. Immediately before obtaining digital images, the stained roots were rinsed thoroughly with water, cut and separated to avoid overlapping roots, and placed on a white tray containing approximately 0.5 cm of H_2O. Root length was calculated using SigmaScan (v2.0) image measurement software. Measurement error with this technique on a known-length string sample was less than 0.5%.

2.3.4. Statistical methods for model testing

Predicted values of soil water content, LAI, and grain yield were analyzed using three statistical properties: the mean deviation (MD), the root mean square error (RMSE), and the coefficient of variation (CV) following Hoogenboom et al. (1999) and Gabrielle et al. (1995).

$$\mathrm{MD} = \frac{1}{n}\sum_{i=1}^{n}(\text{predicted-measured}) \tag{1}$$

$$\mathrm{RMSE} = \left(\frac{1}{n}\sum_{i=1}^{n}(\text{predicted-measured})^2\right)^{0.5} \tag{2}$$

$$\mathrm{CV} = \frac{\mathrm{RMSE}}{x} \times 100 \tag{3}$$

where n is the number of observations and x is the mean of the measured values. The value of MD indicates whether there is a systematic bias in the simulated values. The RMSE reflects the magnitude of the mean difference between predicted and measured values. The CV is a relative measurement of amount of unexplained variation and is independent of the unit of measurement used.

3. Results and discussion

3.1. Post-harvest root distribution

The characteristics of post-harvest root length distribution with depth for the 1997 cropping season were different for the different monitoring sites (Fig. 1). The relationship between root length density and depth to the Bt horizon was apparent. Generally, root length density was greatest in the surface soil and diminished sharply with depth; but for sites with a claypan, root length density increased again with a second peak density occurring 20 cm or further below the top of the Bt horizon.

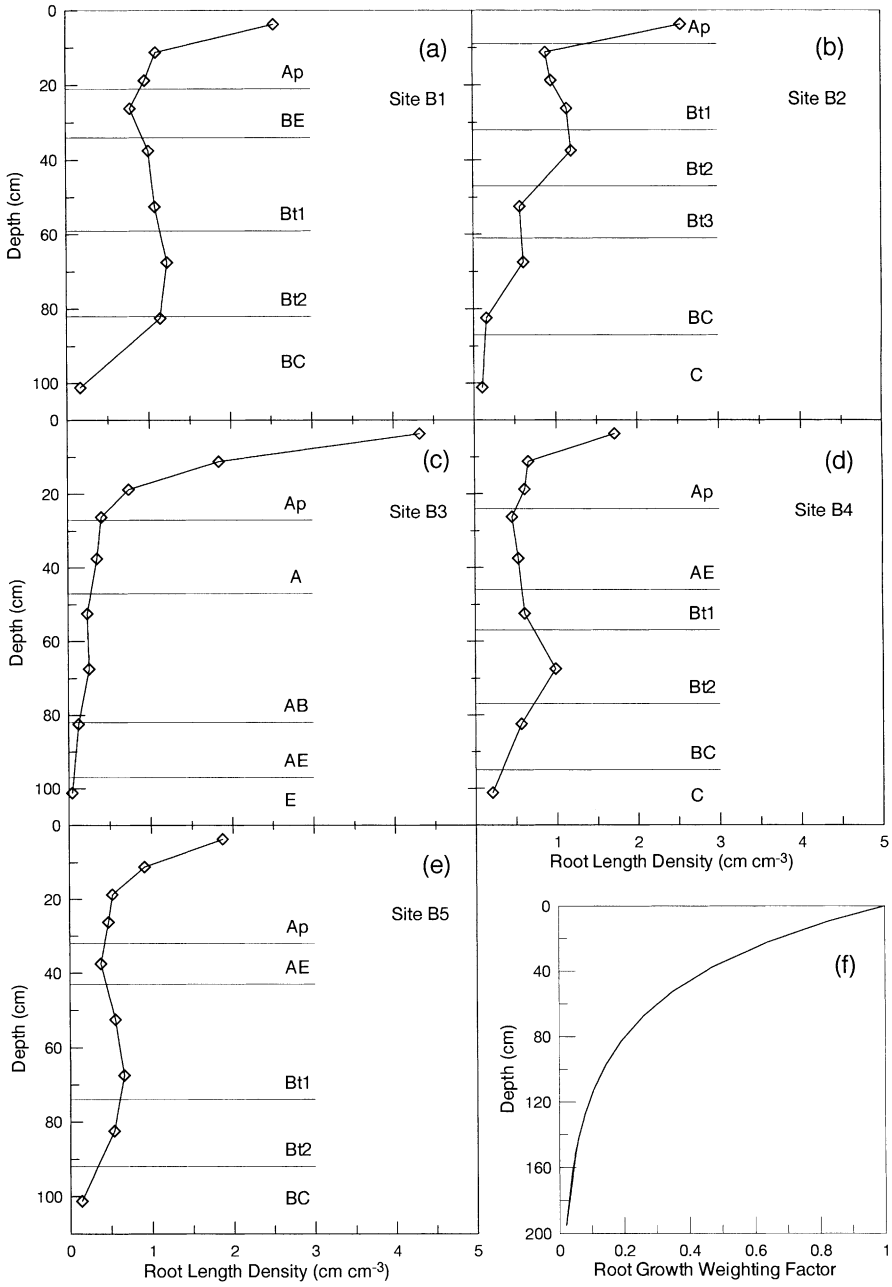

Fig. 1. Distribution of soybean root length density with depth post-harvest in Field B (1997) for (a) B1, (b) B2, (c) B3, (d) B4, (e) B5, and CROPGRO root growth weighting factor in deep, well drained soils with no chemical or physical barriers (f).

The depth and density of soybean root system is an expression of the productivity of the plant. Soybean root development is affected by several environmental factors such as soil bulk density, structure, aeration, and available water content (Mitchell and Russell, 1971). In general, the greater the root density, the greater the rate of soil water removal. Plants normally show greater root density in the upper soil profile. High root density close to the soil surface would allow for rapid water uptake following summer rains. Deeper roots absorb stored water from winter and spring precipitation. A sufficient root density in the lower soil profile is needed by a plant for soil water extraction during dry periods (Tyler and McCutchen, 1980).

The character of the root length density distribution in deep, well-drained soils (Fig. 1c) was very similar to the root growth weighting factor distribution with no chemical or physical barriers (Fig. 1f; Ritchie et al., 1986). Overall, the claypan did not appear to restrict root penetration and development for this year. These results were similar to the results obtained by Keisling et al. (1995) who found that mechanical impedance of tillage pans on silt loam and clay soils to soybean root penetration did not appear to be a problem in a dry growing season. The 1997 accumulated rainfall during the soybean growing season was 428 mm, 15.6% lower than the 59-year average. Soil plant-available water content in claypan soil is always low because of strong matric forces. Our results would indicate that more soybean roots are needed to uptake sufficient soil water in the high-clay layers of the claypan soil.

Root growth parameters (SRGF) were estimated from root length density, soil depth, and type of soil horizon. The SRGF of the Ap horizon was defined as 1.0 for the first 5 cm, with the SRGF for each succeeding depth calculated as the ratio between its root length density and the root length density of the top 5 cm (Table 3). Root length density data were not available for Field A and root growth parameters were estimated by averaging the values estimated for similar horizons in Field B. Because the root growth rates and distribution in different soil layers and at different growth stages are different, it might be better to identify the root distribution characteristics within the growing season instead of post-harvest in future studies.

3.2. Model evaluation

The experimental data sets from sites B1 and B2 of Field B in 1997 and A1, A2, and A3 of Field A in 1998 were used to calibrate the CROPGRO-soybean model. Data collected at sites B3, B4, and B5 during the 1997 season were not used for calibration due to high stand variances in the area sampled. Site B3 was located in a low area of the field that was subjected to ponding in the early spring of 1997 and subsequently replanted. Sites B4 and B5 were located in higher areas of the field but stand variations were caused by ponding in micro-basins located near the selected sites. No data was collected for sites B4 and B5 during the 1999 cropping season due to personnel constraints in addition to fact that sites B1, B2 and B3 provided a good representation of the range of topsoil depths found in field B. In the case of field A, only 1 year of data (1998) was available and half of the sites were used for calibration with the remaining reserved for validation.

The model calibration procedure included two steps. First, soil water lower and upper limits were adjusted so that simulated and measured values of soil water content approximately matched. The ranges for soil water lower and upper limits used are listed in Table 3. Second, genetic coefficients and the soil fertility factor were modified so that model results were similar to measured LAI and yield. The soil fertility factor varied from 0.85 to 1.0 depending on topsoil depth. Calibrated values for the genetic coefficients were quite similar to the default model values for maturity groups 3 and 4 with the exception of the specific leaf area of the cultivar under standard growth conditions (SLAVAR, cm^2/g). This parameter was calibrated at 375.0 and 320.0 for maturity groups 3 and 4, while default values were 350.0 and 350.0, respectively.

3.2.1. Leaf area index

The mean deviation (MD) and the root mean square error (RMSE) between the predicted and measured LAI for each site are shown in Table 4. Overall, the values of MD and RMSE indicated that the model slightly over-predicted LAI in 1997 and 1998 and under-predicted LAI in 1999. The comparisons between the measured and predicted LAI during the growing seasons are shown in Fig. 2. In 1997 predicted LAI was very similar to measured LAI. In 1998 the measured rate of leaf area expansion was high in the mid-vegetative stage, and the predicted maximum LAI

Table 4
MD and RMSE between the predicted and measured leaf area index (LAI)

Site No.	Year	No. of observations	MD (m^2/m^2)	RMSE (m^2/m^2)
Calibration sites				
B1	1997	6	0.2533	0.3978
B2	1997	6	0.2717	0.5267
A1	1998	5	0.3440	0.8603
A2	1998	5	0.1780	1.0233
A3	1998	5	0.3220	1.0441
Average 1997	1997	12	0.2625	0.4622
Average 1998	1998	15	0.2813	0.9759
Overall average	1997–1998	27	0.2719	0.7191
Validation sites				
A4	1998	5	0.0640	1.2476
A5	1998	5	0.1300	1.1795
A6	1998	5	0.0540	1.0141
B1	1999	7	−0.5229	1.0520
B2	1999	7	−0.1886	1.1141
B3	1999	7	−0.0714	0.7890
Average 1998	1998	15	0.0827	1.1471
Average 1999	1999	21	−0.2610	0.9850
Overall average	1998–1999	36	−0.0891	1.0661

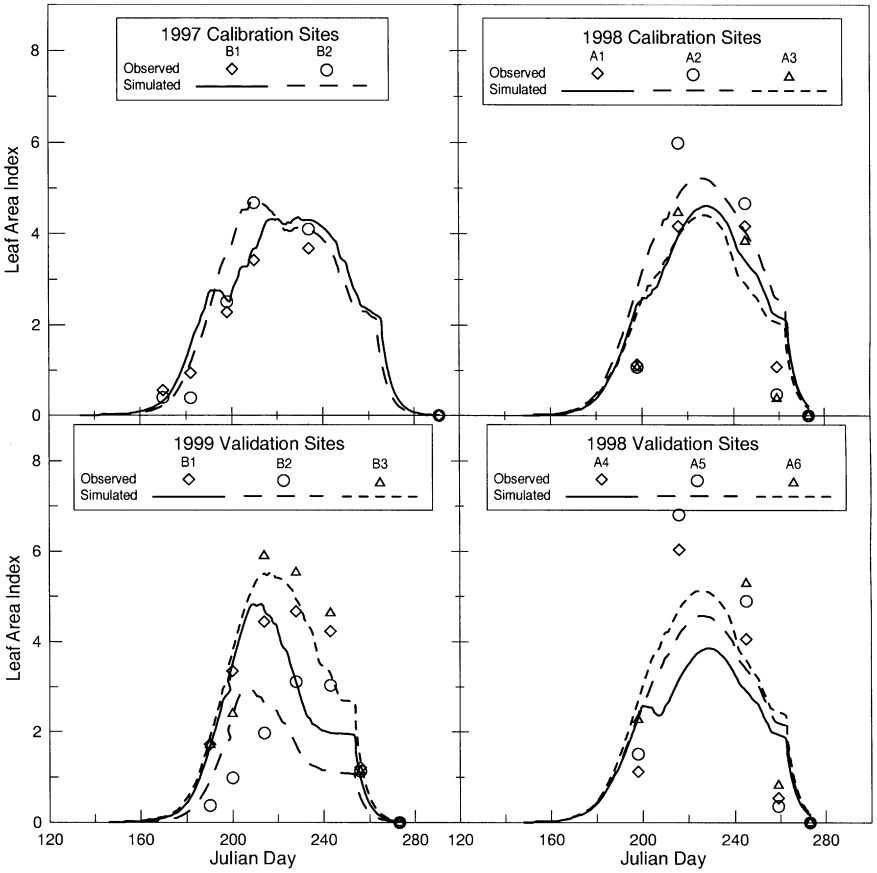

Fig. 2. Measured and predicted leaf area index by year and sites for calibration (top) and validation (bottom) data. Lines are simulated values and the points are the field measurements.

was lower than the measured, thus the RMSE was greater than 1997. In 1999 the accumulated rainfall during the soybean growing season was only 299 mm, 41% less than the 59-year average. The difference between measured and predicted LAI increased after day 210 in 1999. CROPGRO over-estimated the impact of water stress on plant growth during this period. In the model, water deficit affects plant development and the dry matter partition coefficients for shoots and roots (Hoogenboom et al., 1999).

3.2.2. Soil water content

The soil water content results for calibration and validation site-years generally showed good agreement between the predicted soil water content and measured values (Figs. 3–5 and Table 5). The exception to this agreement was Site B3 in 1997. The MD and RMSE at B3 were −0.0668 and 0.1095 cm^3/cm^3, respectively, or about 40 times and 3 times greater in magnitude for MD and RMSE, respectively, than the

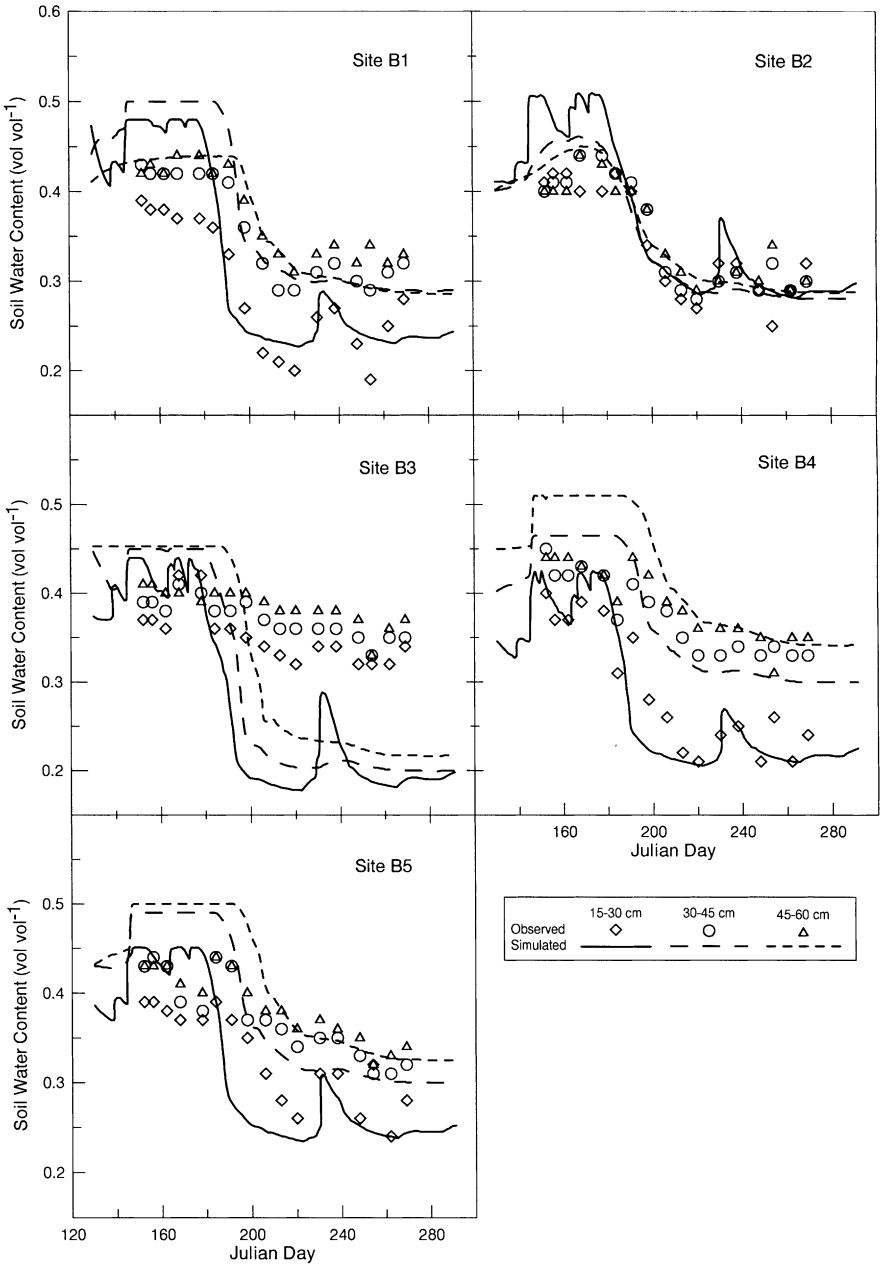

Fig. 3. Measured and predicted soil water content for calibration (B1 and B2) and validation (B3, B4 and B5) sites in Field B in 1997. Lines are simulated values and the points are the field measurements.

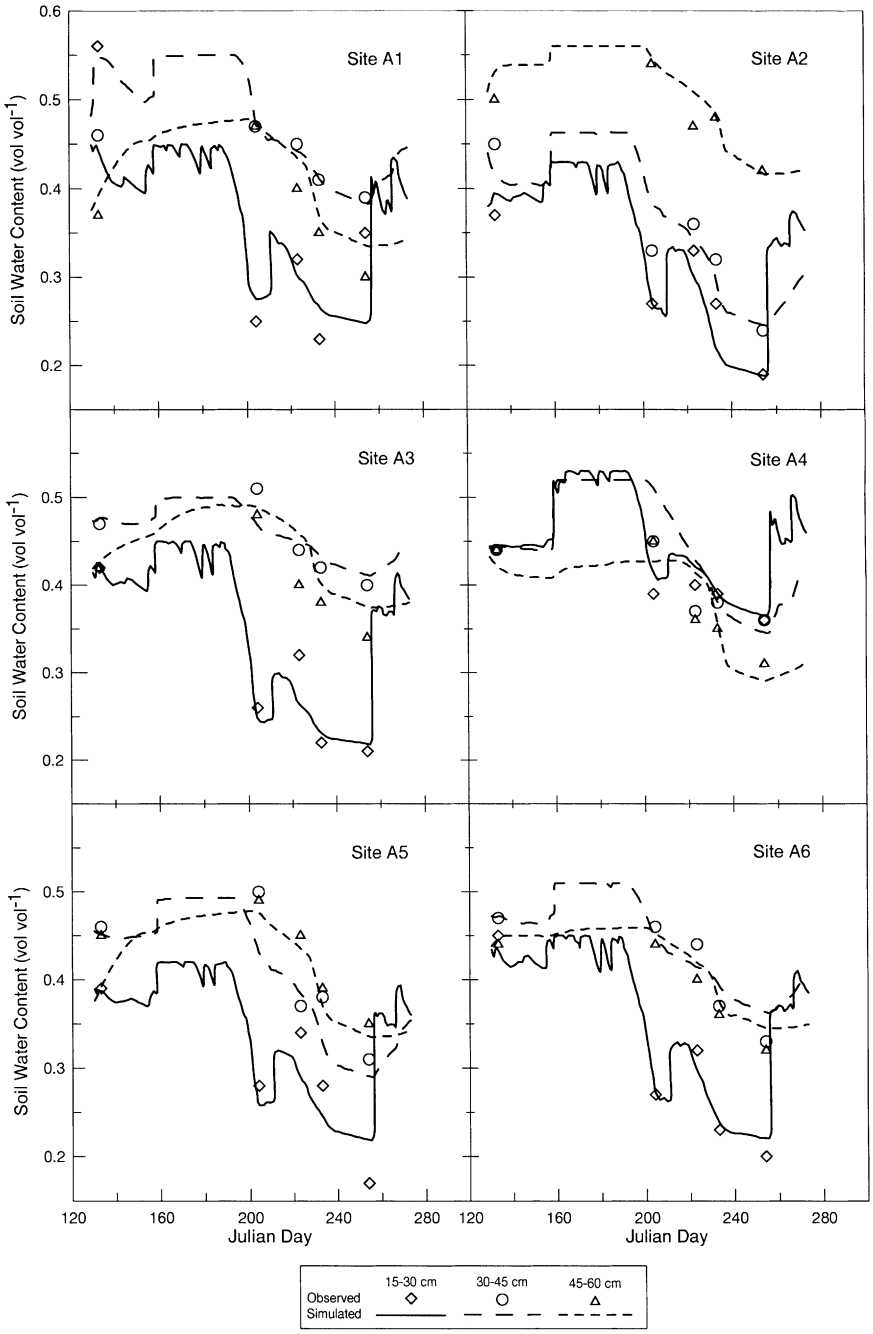

Fig. 4. Measured and predicted soil water content for calibration (A1, A2 and A3) and validation (A4, A5 and A6) sites in Field A in 1998.

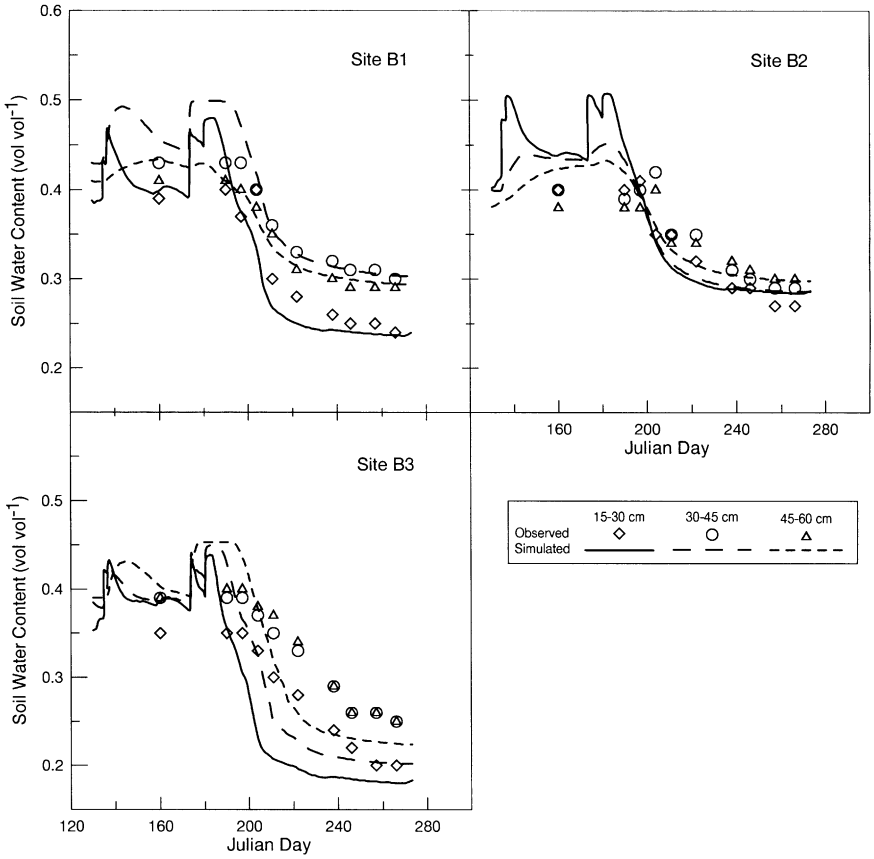

Fig. 5. Measured and predicted soil water content for validation sites (B1, B2, and B3) in Field B in 1999. Lines are simulated values and the points are the field measurements.

average of the other sites and years. This anomaly was the result of the model greatly under-predicting the soil water content for B3 in 1997. Site B3 was located in a lower area of the field and had a topsoil depth over 100 cm (Table 2). We observed ponded water in this footslope area during the spring. Soils with well-developed argillic horizons, known as claypans, are thought to produce considerable amounts of subsurface interflow (Daniels and Hammer, 1992; Kazemi et al., 1993). The shallow topsoil area around site B3 potentially contributed to subsurface flow to this site for days following major rainfall events in addition to surface contributions from upland areas of the field. Since the water balance in the model does not account for any spatially dependent processes, such as lateral surface or subsurface water contributions, we would not expect the model to simulate soil water well in this case.

Both predicted and measured soil water contents were high, and close to the drained upper limits, early in the growing seasons, then decreased over time because of crop water use, evaporation, and drainage. In the upper soil layers, soil water

Table 5
MD and RMSE between predicted and measured soil water contents from 15 to 90 cm

Site No.	Year	No. of observations	MD (cm^3/cm^3)	RMSE (cm^3/cm^3)
Calibration sites				
B1	1997	68	0.0104	0.0445
B2	1997	68	0.0006	0.0351
A1	1998	20	−0.0041	0.0468
A2	1998	20	0.0034	0.0290
A3	1998	20	0.0104	0.0336
Average 1997	1997	136	0.0055	0.0398
Average 1998	1998	60	0.0032	0.0365
Overall average	1997–1998	196	0.0044	0.0381
Validation sites				
B3	1997	68	−0.0668	0.1095
B4	1997	68	0.0165	0.0453
B5	1997	68	0.0041	0.0491
A4	1998	20	0.0147	0.0323
A5	1998	20	−0.0014	0.0329
A6	1998	20	0.0078	0.0207
B1	1999	40	0.0005	0.0235
B2	1999	40	−0.0051	0.0276
B3	1999	40	−0.0321	0.0519
Average 1997	1997	204	−0.0154	0.0680
Average 1997[a]	1997	136	0.0103	0.0472
Average 1998	1998	60	0.0070	0.0287
Average 1999	1999	120	−0.0122	0.0344
Overall average[a]	1997–1999	316	0.0017	0.0367

[a] Without Site B3 in 1997.

content changed rapidly, since each rainfall event obviously influenced the soil water content. In the deeper soil layers the fluctuation of the soil water content was much less.

3.2.3. Soybean grain yield

Soybean yield for each site was predicted for both the calibration and validation data. Generally, there was good agreement between the predicted and measured grain yield (Fig. 6 and Table 6). The model slightly under-predicted yield only for site B2 and over-predicted yield for the other calibration sites. In the model validation, the average MD was 64 kg/ha, and RMSE was 112 kg/ha in 1997 (excluding Site B3 in 1997). If B3 (1997) was included the values were 661.0 and 693.0 kg/ha, respectively. The soybean population at site B3 was very low due to ponding of water early in the 1997 growing season. Therefore, the model severely over-predicted yield at that site.

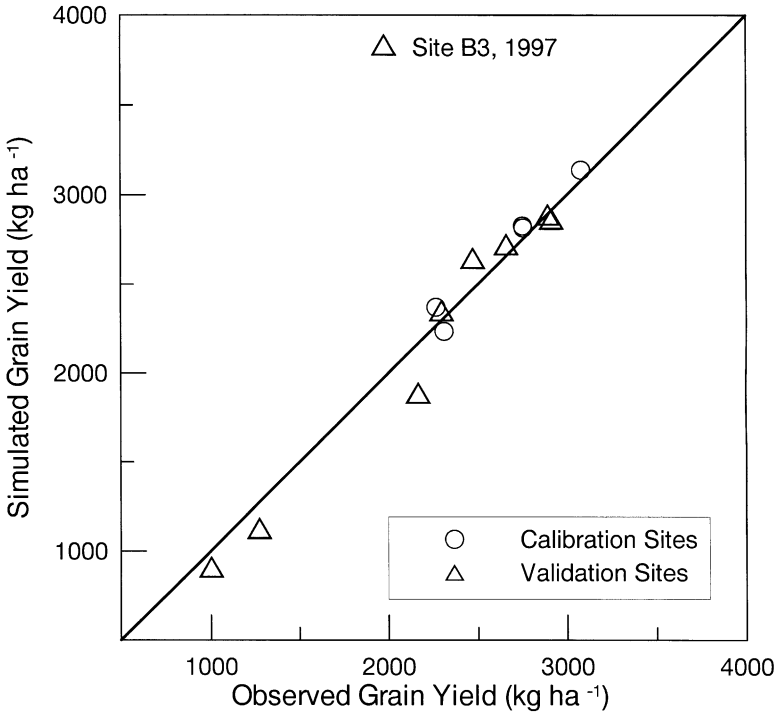

Fig. 6. Comparison between observed and simulated soybean grain yield or calibration and validation data sets.

Our results indicated that the model could predict soybean yield variability across the field under normal growing conditions. In extreme environments, such as the excessively dry year of 1999, the pattern of soybean growth and the dry matter partition coefficients for shoots and roots would be expected to change, causing great variation. Further calibrations of the model parameters for very wet or very dry conditions might improve predictions. However, even without such calibration, mean validation CVs for 1999 were only 11%.

3.3. Grain yield and effects of topsoil depth

Variations of soybean grain yield in relation to topsoil depth under different years are shown in Fig. 7. Overall, soybean yield increased with topsoil depth. Topsoil depth explained 79% of the total variation in predicted grain yield and 28% of the variation in measured grain yield over the two normal precipitation years (1997 and 1998, Fig. 7). Measured yield for site B3 (1997) was not included in the analysis for measured grain yield since a very low stand was the primary factor controlling measured yield at this site. Measured yield in 1999 for site B3 was included, as was simulated yield for this site for both 1997 and 1999. Topsoil depth at this site was significantly greater than at any other monitoring site (Table 2, Fig. 7). The

Table 6
MD, RMSE, and CV between predicted and measured grain yield for calibration and validation sites

Site No.	Year	Predicted (kg/ha)	Measured (kg/ha)	MD (kg/ha)	RMSE (kg/ha)	CV (%)
Calibration sites						
B1	1997	2826	2751	75	75	2.7
B2	1997	2234	2311	−77	77	3.3
A1	1998	2815	2754	61	61	2.2
A2	1998	3139	3079	60	60	1.9
A3	1998	2370	2266	104	104	4.6
Average 1997	1997	2530	2531	−1	76	3.0
Average 1998	1998	2775	2700	75	75	2.9
Overall average	1997–1998	2652	2615	37	76	3.0
Validation sites						
B3	1997	3835	1979	1856	1856	93.8
B4	1997	2646	2471	175	175	7.1
B5	1997	2866	2914	−48	48	1.6
A4	1998	2352	2297	55	55	2.4
A5	1998	2723	2659	64	64	2.4
A6	1998	2890	2893	−3	3	0.1
B1	1999	1128	1274	−146	146	11.5
B2	1999	911	1002	−91	91	9.1
B3	1999	1889	2166	−277	277	12.8
Average 1997	1997	3116	2455	661	693	34.2
Average 1997[a]	1997	2756	2693	64	112	4.4
Average 1998	1998	2655	2616	39	41	1.6
Average 1999	1999	1309	1481	−171	171	11.1
Overall average[a]	1997–1999	2240	2263	−23	108	5.7

[a] Without Site B3 in 1997.

vast majority of the area in both fields had topsoil depths less than 50 cm; therefore all other monitoring sites were chosen with topsoil depths less than 50 cm. However, there was a significant depositional area in each field with topsoil depths of 90 cm or greater that this site was chosen to represent. For 1999, a dryer than average year, the simulated and measured yields for various soil depths were used to derive highly significant ($R^2 \approx 1.0$) linear yield–soil depth relationships. These results support the conclusions of others that topsoil reduction decreases soil fertility and potential water holding capacity, which affects the overall productive capacity of soil (Brubaker et al., 1993; Mulla et al., 1992). As expected, this relationship of topsoil depth and yield was stronger when precipitation was less than adequate. Crop yield measurements from other claypan soil plots have shown crop yield to be strongly related to topsoil depth (Thompson et al., 1991). We concluded that soil water was the main limiting factor for soybean growth in 1999 and that the influence of topsoil depth as it related to water storage and plant availability, significantly affected soybean yield, more than in an average rainfall year. Claypan topsoil depth can be accurately and

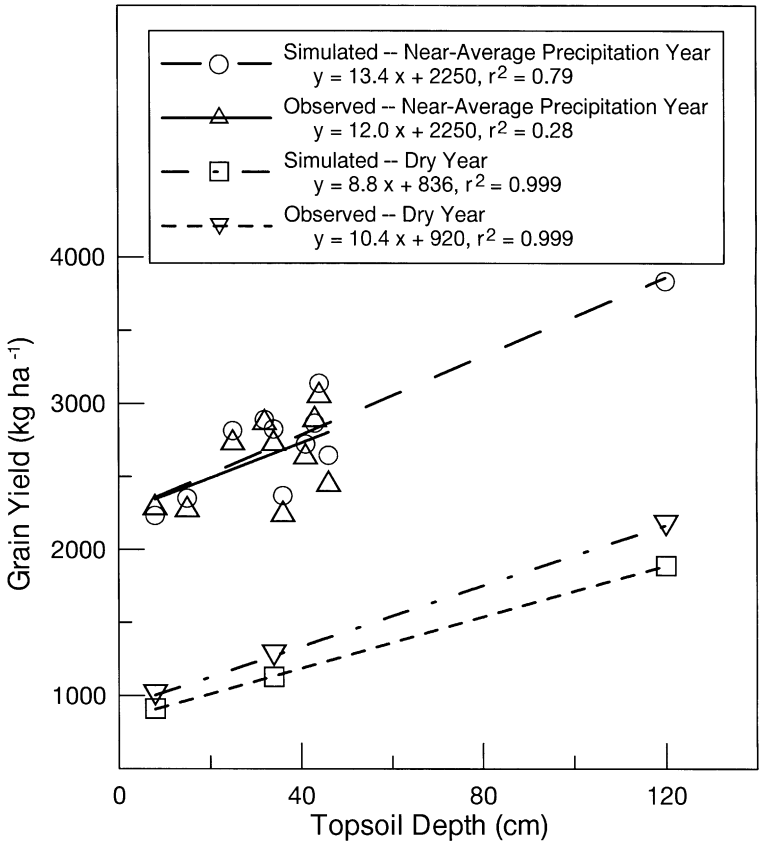

Fig. 7. The variation of soybean grain yield in relation to topsoil depth for years with near-average precipitation and a year dryer than average.

quickly measured over whole fields using on-the-go soil electrical conductivity (EC) sensors (Doolittle et al., 1994; Kitchen et al., 1999; Sudduth et al., 1999). Field-scale yield variation as related to EC-derived topsoil depth has been assessed and found to be significant on water-deficient years (Kitchen et al., 1999).

4. Summary and conclusions

The CROPGRO-soybean model embedded in DSSAT v3.5 was successfully used to simulate leaf area index and soybean grain yield in average-rainfall years for claypan soils. However, the model under-predicted LAI and yield during an extremely dry year because of an unrealistically high simulated water stress factor. Simulated soil water contents within the 15–90 cm soil profile agreed well to the measured values for most sites. However, the model under-predicted soil water for a site that received subsurface flow contributions from upland areas of the field in

average-rainfall years. Since the water balance in the model does not account for any spatially dependent processes, the under-prediction of soil moisture content in areas of the field receiving lateral surface or subsurface water contributions was expected. The claypan did not restrict root penetration; in fact root length density increased within the claypan horizon, perhaps because the soybean plant needed more roots to uptake soil water in high-clay soil layers. However, the additional root density was not enough to overcome the increased resistance to root water uptake caused by higher clay content soils; thus plants in locations with shallower soils topsoil still experienced more water stress and exhibited reduced grain yields. Topsoil depth variations explained 79% of the total variation in model-predicted grain yield in average-rainfall year. In a dry year topsoil thickness influenced yield more than in an average-rainfall year. Overall, the CROPGRO-soybean model can be used as a research tool to explore the effects of complex and alternate management decisions on soybean production.

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