EVALUATION OF RZWQM UNDER VARYING IRRIGATION LEVELS IN EASTERN COLORADO

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ABSTRACT. *The ability to predict and manage crop growth under varying available water conditions is of vital importance to the agricultural community since water is the most important limiting factor for agricultural productivity, especially in semi–arid regions. This study evaluated an agricultural system model, the USDA–ARS Root Zone Water Quality Model (RZWQM), for its ability to simulate the responses of corn (*Zea mays *L.) growth and yield to various levels of water stress. Data sets collected in 1984, 1985, and 1986 in northeastern Colorado were used for model evaluation. Three irrigation levels were imposed in 1984 and four levels in 1985 and 1986. Measurements included soil water content in 1985, leaf area index (LAI) and aboveground biomass in 1984 and 1985, and corn yield and plant height in 1984, 1985, and 1986. The RZWQM was calibrated for the lowest (driest) irrigation treatment in 1985 and then used to predict soil water and agronomic attributes for other irrigation treatments in all three years. Overall, the model responded well to irrigation treatments and weather conditions. Prediction of plant height was adequate in 1985 and 1986. Although biomass was reasonably predicted in early and late growing seasons, it was over–predicted during the middle growing season in both 1984 and 1985. Maximum LAI and plant height were over–predicted in 1984, however. Total soil water storage was well predicted in 1985, and so was evapotranspiration (ET) during the crop growing season. Yield predictions were within 1% to 35% of measured values for all the three years. Even with a low prediction of yield in 1986, the model correctly simulated the relative increase of yield with irrigation amount. Therefore, once RZWQM is calibrated for a location, it can be used as a tool to simulate relative differences in crop production under different irrigation levels and as a guide to optimize water management.*

Keywords. *Corn, Irrigation, Modeling, Water stress, Yield.*

World agricultural productivity is heavily dependent on water availability, and water management is one of the most important components in modern agriculture. Sound water management in the field and real–time responses to soil water availability usually determine success or failure for many farmers. There is an urgent need for management tools to guide producers to optimize agricultural productivity under unfavorable environmental conditions. A well tested agricultural system model can be used to evaluate different management scenarios and risks associated with soil and climate conditions (Matthews et al., 2002). Examples of system models are the CERES family of crop growth models (Ritchie et al., 1998), CROPGRO (Boote et al., 1998), EPIC (Williams, 1995), CropSyst (Stockle et al., 1994), RZWQM (Ahuja et al., 2000), and Ecosys (Grant, 2001). Although most of the models are still research tools within the scientific community and have not been utilized by producers for real–time management, they have advanced our understanding of the complex agricultural system for management and are ready for such applications (Ahuja et al., 2002, pp. 357; Matthews et al., 2002).

The Root Zone Water Quality Model (RZWQM), described by Ahuja et al. (2000), is a system model with components for plant growth, water movement, chemical transport, and nitrogen/carbon dynamics with management effects as the centerpiece. It has been evaluated under a variety of conditions (Ma et al., 2000a). So far, RZWQM has been parameterized for corn and soybean. Simulations of corn using RZWQM have been reported for studies in Iowa (Bakhsh et al., 2001; Jaynes and Miller, 1999), Colorado (Ma et al., 1998; Farahani et al., 1999), Ohio (Landa et al., 1999; Nokes et al., 1996), Nebraska (Martin and Watts, 1999), and Missouri (Ghidey et al., 1999). The model was tested for soybean production in Colorado (Nielsen et al., 2002), Iowa (Jaynes and Miller, 1999), Missouri (Ghidey et al., 1999), and Ohio (Landa et al., 1999). Evaluation of these studies was reported by Ma et al. (2000a).

Among these studies, Martin and Watts (1999) used RZWQM to investigate corn production under different irrigation and nitrogen rates from 1992 to 1994. The model provided adequate simulations of plant biomass for all the years and treatments. Simulated leaf area index was reasonably good except for 1994 when wind damage was plausible.

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Grain yield was over–predicted except for 1992, the calibration year. Responses of grain yield to irrigation water were poor in general, even in 1992. Nielsen et al. (2002) used the most recent (improved) version of RZWQM and presented an application of RZWQM for a soybean study conducted in eastern Colorado in 1985 and 1986 under three watering systems (gradient line–source, rain shelter, and drip) and four irrigation treatments. They found that RZWQM–simulated soybean yield responded well to irrigation water under all the irrigation systems in both 1985 and 1986.

To further evaluate the applicability of the improved RZWQM version for corn production and responses to irrigation water under the Great Plains semi–arid conditions, a data set from the USDA–ARS Central Great Plains Research Station in Akron, Colorado, was selected. The experiment was designed to evaluate corn production by irrigating only a week before tasseling to maximize water use efficiency (Denmead and Shaw, 1960; Waldren, 1983). The specific objective of this article was to test RZWQM for water stress responses of corn grown under various limited irrigation treatments using the above data set. This is part of an effort for using RZWQM to simulate agricultural management effects and for developing an information database for decision support purposes.

MATERIALS AND METHODS

Experiments were conducted during the 1984, 1985, and 1986 growing seasons at the USDA Central Great Plains Research Station, 6.4 km east of Akron, Colorado (40° 9′ N, 103° 9′ W, 1384 m a.m.s.l). The soil type is a Rago silt loam (fine, smectitic, mesic Pachic Argiustoll). Soil texture was analyzed with the hydrometer method (Gee and Bauder, 1986) and is shown in table 1.

Corn was planted on 14 May 1984, 3 May 1985, and 1 May 1986, with corresponding seeding densities of 72400, 76100, and 76100 seeds/ha. Prior to each planting, the plot area (36.6 m × 24.4 m) was fertilized with ammonium nitrate at a rate of 168 kg N ha^{-1}. Corn (Pioneer Hybrid 3732, 101–day, growing degree days to silking and maturity [base 10° C] = 500 and 1336, respectively) was grown under a line–source gradient irrigation system, with full irrigation next to the irrigation line and linearly declining water application with distance from the line. Details regarding the irrigation system can be found in Nielsen (1997). Four replicates of four irrigation levels (only three irrigation levels in 1984) existed along the line–source system, with a soil water measurement site and irrigation catch gauge at each of the 16 identified sampling sub–plots (12 in 1984). Irrigations were initiated just prior to tasseling (stage VT; Ritchie et al., 1986) in each year. The total number of irrigation events was 5 from 20 July to 2 September 1984, 11 from 29 June to 22 August 1985, and 10 from 21 July to 26 August 1986. Total irrigation water applied ranged from 23 to 106 mm in 1984, from 72 to 188 mm in 1985, and from 146 to 299 mm in 1986 (table 2). The irrigation application rate was 3.2 mm hr^{-1}.

Table 1. Measured soil texture of the Rago soil.

Soil Depth (m)	Soil Bulk Density (Mg m^{-3})	Sand (%)	Silt (%)	Clay (%)	Water Content at 33 kPa (W33) (m^3 m^{-3})	Saturated Hydraulic Conductivity (K_{sat}) (mm hr^{-1})
0–0.30	1.33	39	42	19	0.233	96.7
0.30–0.60	1.33	32	44	24	0.233	96.7
0.60–0.90	1.36	37	41	22	0.192	140.8
0.90–1.20	1.40	46	37	17	0.192	118.7
1.20–1.50	1.42	46	42	12	0.192	108.0
1.50–1.80	1.42	48	42	10	0.192	108.0

Table 2. Irrigation timing and amount (mm) for the line–source gradient irrigation system from 1984 to 1986.

	Irrigation Level (mm)			
Date	1	2	3	4
1984				
20 July	6	20	30	—
30 July	4	12	20	—
20 August	4	11	17	—
25 August	3	8	14	—
21 September	6	17	25	—
Total	23	68	106	—
1985				
29 June	3	3	4	5
30 July	34	34	58	76
8 August	3	5	7	9
9 August	1	1	2	2
12 August	8	14	21	25
14 August	3	5	8	10
15 August	5	9	14	17
17 August	3	5	7	9
19 August	4	6	10	12
20 August	4	6	10	11
22 August	4	6	10	12
Total	72	98	151	188
1986				
21 July	12	18	24	28
23 July	13	20	24	28
25 July	12	17	23	31
29 July	12	15	19	21
4 August	18	23	26	25
6 August	17	25	30	30
12 August	12	15	20	23
19 August	13	19	26	33
20 August	15	19	28	40
26 August	22	32	38	40
Total	146	203	258	299

Soil water measurements were made at planting and harvest, and at several other intermediate times during the growing season in 1985. These measurements were made at 0.15, 0.45, 0.75, 1.05, 1.35, and 1.65 m below the soil surface with a neutron probe calibrated against the 96 soil water samples taken at the time of access tube installation (six depths at 16 measurement sites). Neutron probe readings were then converted to soil water contents for each soil horizon. Crop water use in terms of evapotranspiration (ET) was calculated as the difference in soil water storage in the soil profile plus precipitation and irrigation during the sampling interval. No runoff was observed in the experimental plots. There were no measurements of percolation, but we assume percolation below the root zone to be minimal due to the low irrigation amounts.

Leaf area measurements were made periodically during the 1984 and 1985 growing seasons by destructively sampling 1 m of crop row, separating leaves from the stalks, and measuring the leaf area with a leaf area meter (Li–Cor model LI–3100, Lincoln, Neb.). Aboveground biomass was measured on the same samples after 48 hours of drying at 50° C. Plant height was measured on six plants at each soil water measurement site at approximately weekly intervals in 1984, 1985, and 1986. Yield (reported at 0% moisture) was sampled at harvest (1 October 1984, 27 September 1985, and 15 October 1986) from a 6.1–m length of row centered on each soil water measurement site. An automated weather station recorded air temperature, wind run, solar radiation, rainfall, and relative humidity approximately 300 m from the experimental plots.

THE PLANT GROWTH COMPONENT OF RZWQM

The model name, Root Zone Water Quality Model (RZWQM), originated from the collaboration with the MSEA (Management System Evaluation Areas) water quality project in the U.S. Midwest (Watts et al., 1999). RZWQM is a whole agricultural system model that includes major physical, chemical, and biological processes. Plant growth is an essential part of RZWQM and it links various processes in the system. Many of the processes have been evaluated and documented (Ahuja et al., 1993, 2000; Ma et al., 1998; RZWQM Team, 1998) and will not be presented here. A complete description of plant processes is available in Hanson (2000). The uniqueness of the plant growth component is that it simulates both individual plant growth and population development.

Individual Plant Growth

As in other plant growth models, the plant growth module of RZWQM assumes an ideal plant growth scenario and then modifies the scenario based on temperature, water, and nutrient (nitrogen) stresses. Plant growth is driven by photosynthesis, which is a function of solar radiation only (Hanson, 2000). Assimilated carbon is stored in an allocatable carbon pool and then partitioned among root, leaf, stem, and propagule. Seed biomass is transformed from the propagule biomass pool. Nitrogen demand is estimated from the carbon/nitrogen (C/N) ratio of each plant component and met by root uptake through mass flow in the transpiration stream, supplemented by active uptake to an extent if nitrogen demand cannot be met. The model gives priority to seed production (over, for example, growth of existing leaves and roots, or increasing number of leaves and roots) when adverse environmental conditions occur. Many of the simulated processes are controlled by environmental factors.

RZWQM simulates effects of three environmental factors: temperature, water, and nitrogen. Water stress factor is calculated from the ratio of actual to potential transpiration (1 – AT/PT). Temperature stress factor is based on minimum, maximum, and optimum growth temperatures. Two N stress factors are defined in RZWQM. One is the whole–plant N stress factor, which is calculated from N demand and current N concentration in a plant. The other is the leaf N stress factor, estimated from actual leaf nitrogen content in relation to predefined minimum and maximum leaf nitrogen contents at a growth stage. Details are available in Hanson (2000). Physiological processes are made a linear or nonlinear function of either the total environmental fitness factor or individual fitness factors, as appropriate for the process and growth stage. These processes include daily photosynthesis rate, daily shoot death, and root/shoot ratio. A separate soil water stress factor on root growth was adopted from the CERES–Maize model (Jones et al., 1991).

Phenological development in RZWQM is divided into dormancy, germination, emergence, 4–leaf, vegetative growth, and reproductive growth. Instead of using degree–days to measure progression from one phenological stage to another, RZWQM adopted the minimum days (MD) concept, in which a plant has to accumulate a certain number of days before advancing to another stage under optimum conditions. Actual days needed between stages depend on temperature, water, and N stresses. Although the minimum days concept is different from the minimum degree–days approach, temperature effect is accounted for by using a temperature fitness factor (Hanson, 2000).

Population Development

Besides individual plant growth simulation, RZWQM also simulates plant population development using a modified Leslie matrix model (Hanson, 2000). The Leslie matrix model assumes that a population life history can be divided into a given number of discrete classes, with each class including a class–specific fecundity rate and a probability of surviving to the next age class. In the modified approach, a probability of staying in the same class at the end of each day is assumed (Hanson, 2000). Each individual plant goes through seven phenological growth stages: dormancy, germination, emergence, 4–leaf plant, vegetative growth, reproductive growth, and senescence. The number of plants in each phenological stage is controlled by the Leslie matrix. Progression of each plant from one stage to another depends on genetic characteristics of the plant and environmental fitness (water, temperature, and nitrogen stresses) (Hanson, 2000).

CALIBRATION OF RZWQM

Calibration of system models is one of the most challenging areas in model application, since often a number of required parameters are not easily measurable (Ahuja and Ma, 2002). It is particularly true for process–level models like RZWQM, and there is a need for developing systematic calibration procedures for agricultural system models. Although Ahuja and Ma (2002) outlined the basic principles for calibrating RZWQM, actual steps may vary from application to application, depending on data availability and emphasis of calibration. Calibration of RZWQM is an iterative process (fig. 1). Generally speaking, more extensive experimental measurements help identify better model parameters and decrease the degree of freedom in parameter optimization. The RZWQM developers made extensive efforts to provide default parameters whenever possible. For example, distribution of the RZWQM includes: a database for calculating soil hydraulic properties from soil texture, a pesticide database, and previously tested plant growth parameters. The model can be run with very minimal input (Ahuja and Ma, 2002). In this study, goodness of model calibration is evaluated with root mean square error (RMSE) and a normalized objective function (NOF) (Ahuja and Ma, 2002). NOF is defined as ($RMSE/O_{avg}$), where O_{avg} is the average observed value.

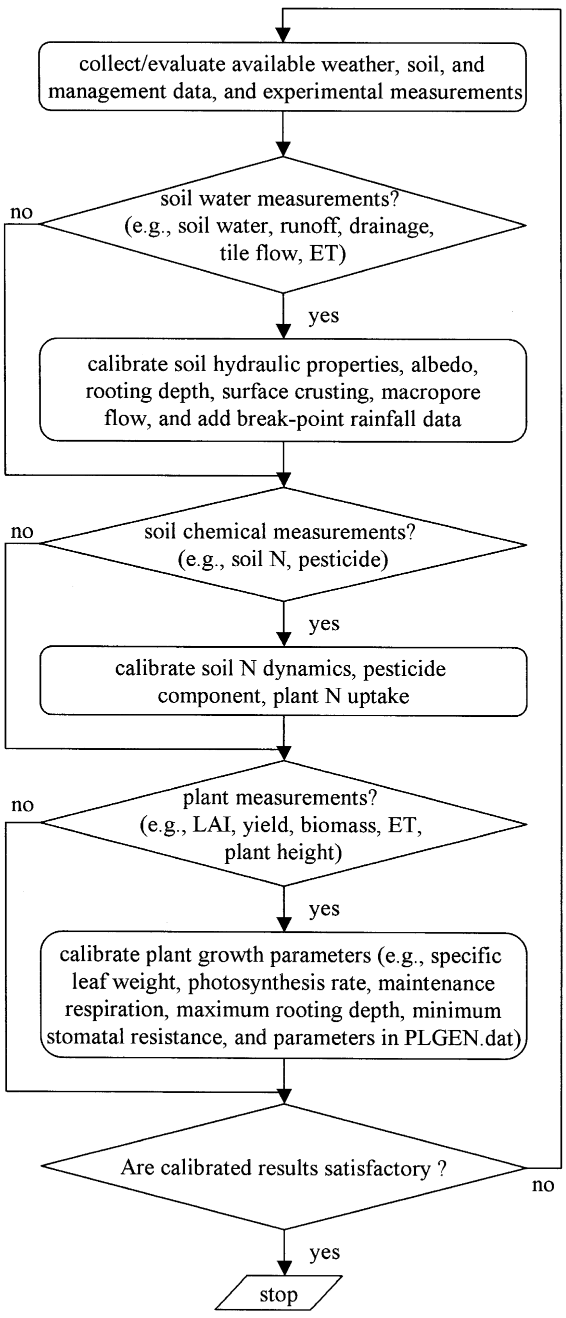

Figure 1. The iterative calibration procedure of RZWQM.

In this experiment, the most complete data were collected in 1985. Therefore, the RZWQM was calibrated for 1985, when soil water content, leaf area index (LAI), plant height, aboveground biomass, evapotranspiration (ET), and grain yield were measured. Furthermore, we selected the lowest irrigation level (level 1 in table 2) in 1985 for calibration purposes. Meteorological data (daily maximum and minimum air temperature, rainfall, solar radiation, wind run, and relative humidity) were obtained from the nearby automated weather station. Soil texture and bulk density were determined from sampled soil cores. Management practices were recorded. Because no obvious N deficiency was observed in the field, we assumed N stress was negligible and evaluated water stress only. The parameters obtained from the calibration process were then used to predict corn production for the other irrigation levels in 1985 as well as for the three irrigation levels in 1984 and the four irrigation levels in 1986.

Following the diagram in figure 1, the model was calibrated for soil water first and then for crop growth since no soil N and plant N uptake data were measured. The soil water retention curve is described using the Brooks–Corey equation in RZWQM, and the Brooks–Corey parameters were taken from table 2 of Rawls et al. (1982) for the loam soil based on the soil texture shown in table 1. Although the soil is classified as a silt loam, Peterson et al. (1986) showed that the Rago soil can range from silt loam to sandy loam depending on location. The saturated hydraulic conductivity (Ks) for each layer was obtained from the Ks–effective porosity relationship derived by Ahuja et al. (1989). Unsaturated hydraulic conductivity was then calculated from Ks and the water retention curve parameters utilizing the approach of Campbell (1974). Using these texture–averaged hydraulic parameters provided reasonable simulations of soil water with an RMSE of 0.0228 m^3 m^{-3}.

To further improve soil water predictions, we calibrated soil water content at 33 kPa (W33), which is an option in RZWQM. The W33 calculated from the default Brooks–Corey parameters is 0.233 m^3 m^{-3} for a loam soil. Since the deepest two soil layers (1.20–1.80 m) are on the boundary between sandy loam and loam, we used the calculated W33 for a sandy loam soil (0.192 m^3 m^{-3}) for the deepest soil layers instead of 0.233 m^3 m^{-3}. When a different W33 is given, other than the one calculated from the default Brooks–Corey parameters, RZWQM will automatically scale the soil water retention curve using a similar–media scaling technique (Ahuja et al., 1985). We found that when a W33 of 0.192 m^3 m^{-3} was used for the lowest two soil layers, the RMSE was reduced to 0.0207 m^3 m^{-3}. As we further replaced W33 for the soil layer of 0.90–1.20 m, the RMSE was reduced to 0.0185 m^3 m^{-3}. The lowest RMSE of 0.0166 m^3 m^{-3} was obtained when W33 was 0.233 m^3 m^{-3} for the top two soil layers (0–0.60 m) and 0.192 m^3 m^{-3} for the deeper four layers (0.60–1.80 m). No further calibration was made for W33 since the lowest RMSE resulted in a NOF value of 0.108, which is comparable to (in fact, better than) field soil water content measurement errors.

Calibration of the plant growth parameters was based on studies conducted previously to test the model for corn in Colorado (Farahani et al., 1999). All the plant parameters used in Farahani et al. (1999) are part of the database provided with the current release version of RZWQM (Rojas et al., 2000). Table 3 lists some of the plant parameters that are corn variety–sensitive and are suggested to calibrate or measure (Hanson et al., 1999; Ma et al., 2000a, 2000b). Minimum leaf stomatal resistance was reduced from 250 to 100 s/m based on literature reports (Fiscus et al., 1991; Bennett et al., 1987). Aboveground biomass of a mature plant was calculated from measured biomass and plant population. When the maximum potential rooting depth of 1.80 m from Farahani et al. (1999) was used for this study, the RMSE for simulated soil water contents was 0.0261 m^3 m^{-3} and ET was 360 mm from 13 June to 25 September 1985, as compared with 439 mm estimated from soil water balance. Actual simulated rooting depth reached only up to 1.28 m. So we increased the maximum (potential) rooting depth to 3.00 m to increase root penetration without changing other root growth–related parameters (Ahuja and Ma, 2002). Actual rooting depth was 1.78 m. Maximum plant height and

Table 3. Calibrated plant model parameter values of RZWQM for corn. Parameters with asterisk (*) are suggested calibration parameters by the model developers.

Parameter	Values from Farahani et al. (1999)	Values from RZWQM calibration in this study
Minimum leaf stomatal resistance (s/m)*	250	100
Proportion of photosynthate lost to respiration (dimensionless)*	0.28	0.28
Photosynthesis rate at reproductive stage compared to vegetative stage (fraction)*	0.78	0.65
Photosynthesis rate at seeding stage compared to vegetative stage (fraction)*	0.78	0.65
Coefficient to convert leaf biomass to leaf area index, CONVLA (g/LAI)*	12.5	13.5
Plant population on which CONVLA is based (plants/ha)*	79800	79800
Maximum rooting depth (m)*	1.80	3.00
Maximum plant height (m)	2.50	2.10
Aboveground biomass at 1/2 maximum height (gm)	30	60
Aboveground biomass of a mature plant (gm)	70	152
Minimum time needed from planting to germination (days)	5	4
Minimum time needed from germination to emergence (days)	15	16
Minimum time needed from emergence to 4–leaf stage (days)	20	17
Minimum time needed from 4–leaf stage to end of vegetative growth (days)	30	40
Minimum time needed from end of vegetative to end of physiological maturity (days)	40	43

biomass at 1/2 maximum height were calibrated manually based on measured plant height (table 3).

We also found that the minimum days between phenological stages used by Farahani et al. (1999) were arbitrarily derived (manually) and did not provide adequate predictions for this study. Therefore, an optimization scheme was developed to calibrate these minimum days. Although the corn variety used in this study was characterized as 101–day corn under optimum conditions for the test location (Nielsen and Hinkle, 1996), the minimum growing days could vary from location to location. The minimum days (MD) required between phenological stages were varied around those used by Farahani et al. (1999) (table 3), specifically: 2–8 days from dormancy to germination (MD1), 10–20 days from germination to emergence (MD2), 15–25 days from emergence to 4–leaf (MD3), 25–40 days from 4–leaf to end of vegetative growth (MD4), and 35–45 days from end of vegetative to end of productive growth (MD5), while keeping total MD (TMD = MD1 + MD2 + MD3 + MD4 + MD5) at either 100, 105, 110, 115, or 120 days. Using the Ordered Partitions function in GAP (GAP, 2002), a total of 2125, 4948, 7309, 7309, and 4948 combinations of {MD1, MD2, MD3, MD4, MD5} were generated for TMD of 100, 105, 110, 115, and 120 days, respectively. To reduce the number of runs, we picked 500 combinations randomly for each TMD using the Random Function in GAP, which uses algorithm A in section 3.2.2 of Knuth (1998). The best combination of {MD1, MD2, MD3, MD4, MD5} was selected based on average NOF values from predicted soil water content, LAI, plant height, ET, aboveground biomass, and grain yield (table 3).

Results

Temperature and Precipitation Conditions

Total annual rainfall was 472, 454, and 330 mm for 1984, 1985, and 1986, respectively. Total growing season rainfall (May through September) was 299, 317, and 205 mm for 1984, 1985, and 1986, respectively. Most days in the critical pre–silking through mid–grain filling period (DOY 195–240, 14 July to 28 August) had maximum temperatures above 30° C, typical of high evaporative demand days. The precipitation during this same critical developmental period was 136, 138, and 240 mm for 1984, 1985, and 1986, respectively, while pan evaporation was 439, 426, and 463 mm, respectively. To further document the existence of water stress conditions in our three years of data, we used the Penman–Monteith equation and previously established crop coefficient relationships (Jensen et al., 1990; Nielsen and Hinkle, 1996) to calculate the growing season non–water–stressed corn water use of 545 mm in 1984, 554 mm in 1985, and 564 mm in 1986.

Experimental Results

Average grain yields ranged from 3.2 to 6.9 Mg ha^{-1} in 1984, from 6.9 to 9.9 Mg ha^{-1} in 1985, and from 6.6 to 10.3 Mg ha^{-1} in 1986. Since the irrigation treatments were not randomized, no statistical analysis was performed. Measured leaf area index (LAI) and biomass for 1984 and 1985 were not remarkably different among irrigation levels (figs. 2 and 3), however. Greater variability of the results among the treatments in 1984 than in 1985 was not explainable. Because water treatments affected mostly corn yield, good model prediction of grain yield was one of the key criteria. Since no runoff was observed in the experimental plots, and leaching below the 1.80–m soil profile was unlikely based on a 3.2 mm hr^{-1} irrigation rate and a maximum 76 mm per event (table 2), measured soil water contents were used to estimate evapotranspiration (ET) during the 1985 growing season. Estimated ET from 13 June to 25 September 1985 was 398, 410, 487, and 506 mm for the four irrigation levels, respectively. Estimated non–water–stressed corn water use for the same period was 505 mm. Therefore, total rainfall and irrigation amount for the wettest treatment should meet the water demand from 13 June to 25 September, but not for the other irrigation levels.

Model Calibration Results (1985, Irrigation Level 1)

Calibrated model parameters are listed in table 3. Leaf area index, plant height, and aboveground biomass (dry weight) were simulated well by RZWQM for the calibration data set (figs. 4, 5, and 6). There was an underestimation of plant height early in the growing season (prior to DOY 180),

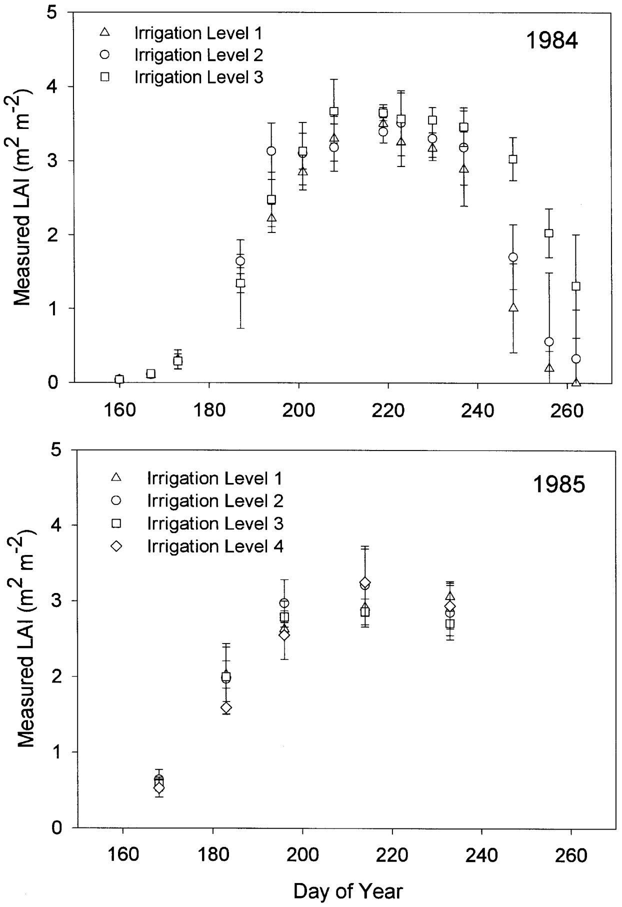

Figure 2. Measured leaf area index (LAI) in 1984 and 1985 for all the irrigation levels. Bars are one standard error around the mean values.

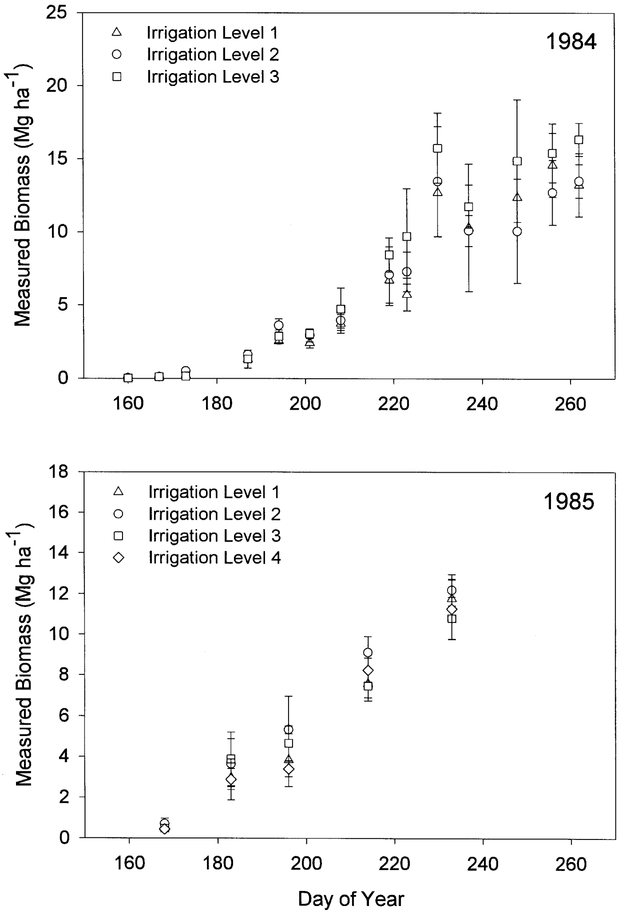

Figure 3. Measured aboveground biomass in 1984 and 1985 for all the irrigation levels. Bars are one standard error around the mean values.

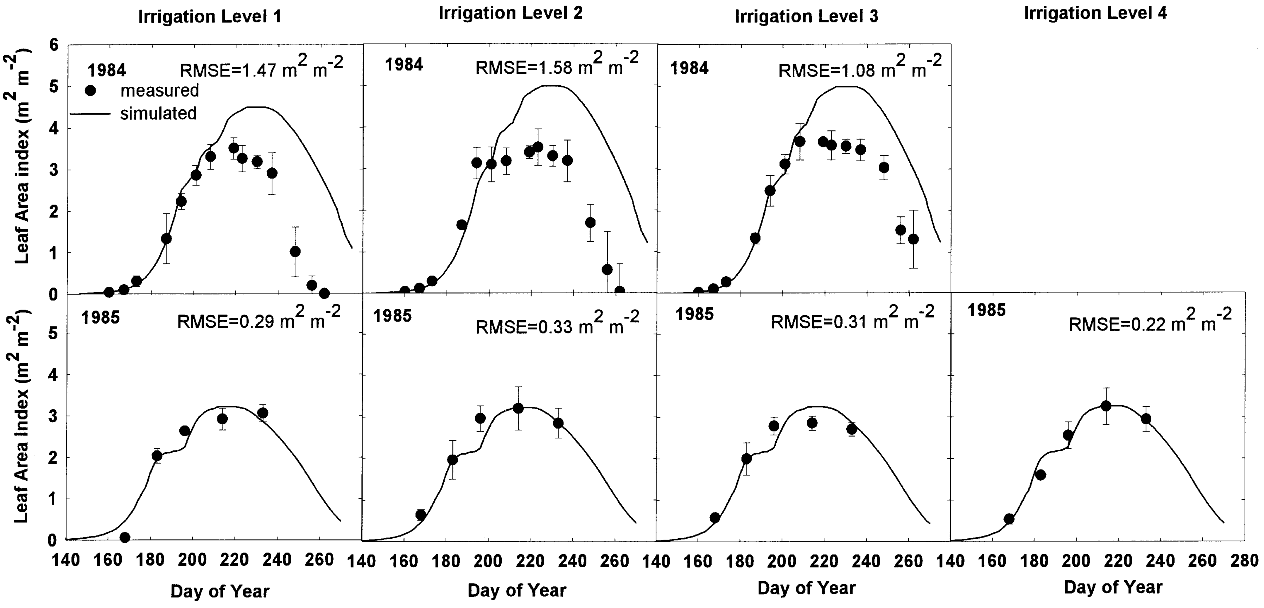

Figure 4. Measured and simulated corn leaf area index in 1984 and 1985. Vertical bars are one standard deviation around the mean values. See table 2 for corresponding irrigation amounts at each level.

and biomass was overestimated near the end of the growing season by 14%. Simulated evapotranspiration (ET) from 13 June to 25 September 1985 was underestimated by 9% (fig. 7). As shown in figure 8, the model fairly consistently overestimated the total amount of water in the soil profile (average over–prediction of 5.5%). Soil water storage could be improved further if we had conducted a more extensive calibration of the soil hydraulic properties rather than taking

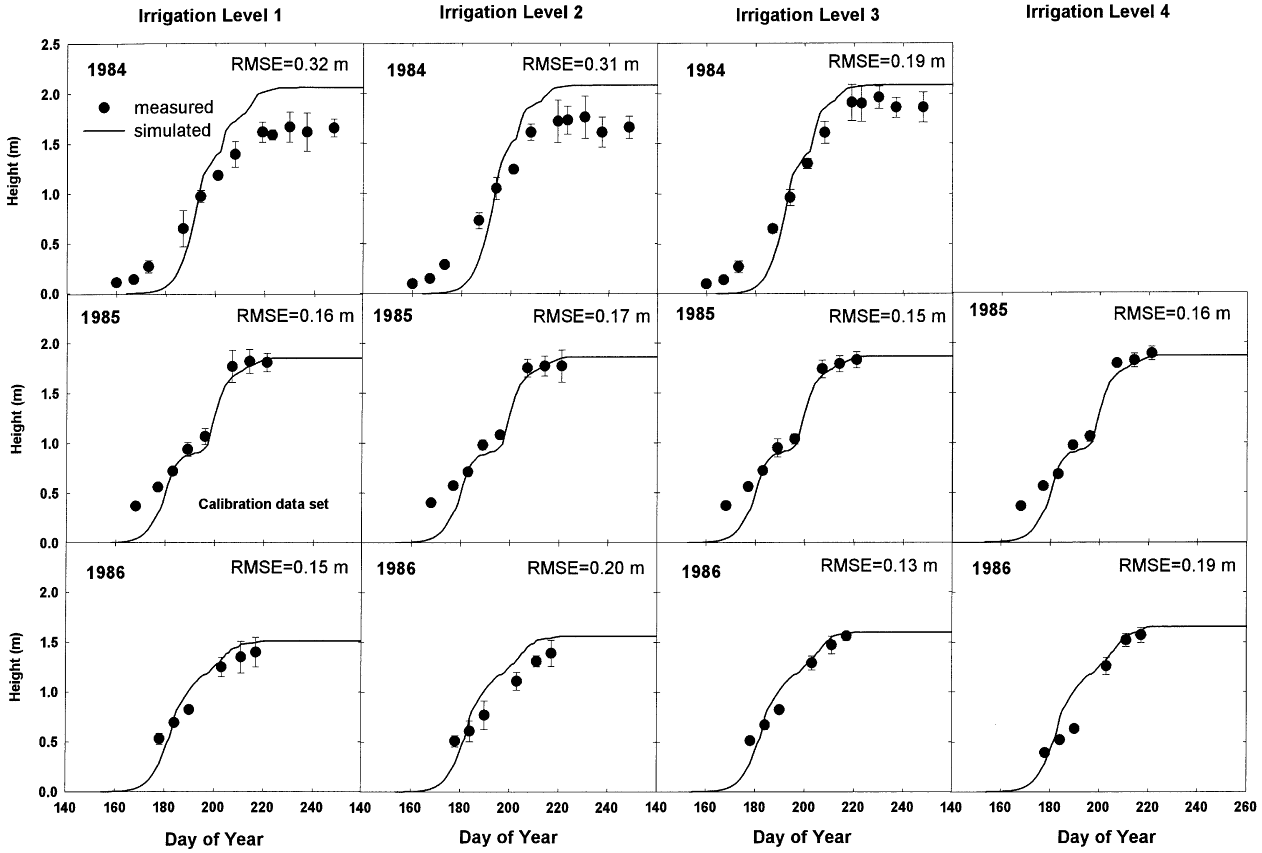

Figure 5. Measured and simulated corn height in 1984, 1985, and 1986. Vertical bars are one standard deviation around the mean values. See table 2 for corresponding irrigation amounts at each level.

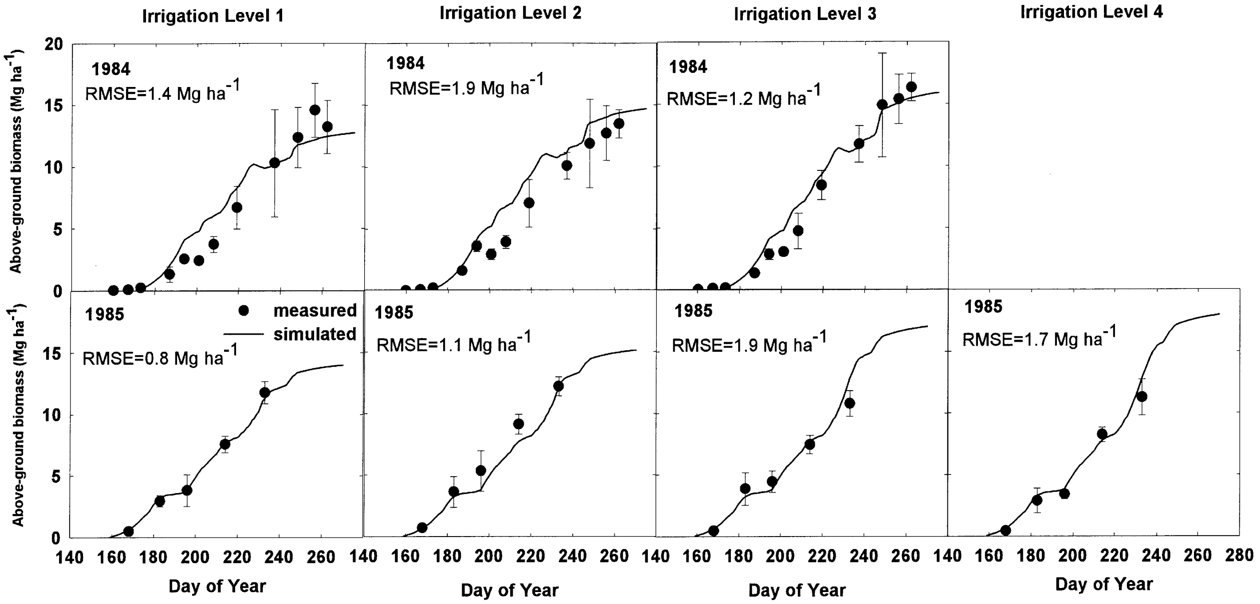

Figure 6. Estimated (from soil water balance) and simulated aboveground corn biomass in 1984 and 1985. Vertical bars are one standard deviation around the mean values. See table 2 for corresponding irrigation amounts at each level.

the default W33 for loam and silt loam soils. Grain yield was adequately calibrated as well (fig. 9). The field–observed silking date was 26 July 1985, and RZWQM predicted 16% of the plant population entering reproductive stage on that day. The model simulated zero runoff and 0.7 mm of drainage out of the 1.80–m soil profile, which agrees with our assumption for ET estimation from soil water balance, so we can compare this estimated ET with RZWQM–simulated ET from the Shuttleworth–Wallace model (Shuttleworth and Wallace, 1985). The model did not simulate any water stress prior to 29 June 1985. Water stress was reduced with irrigation and rainfall events.

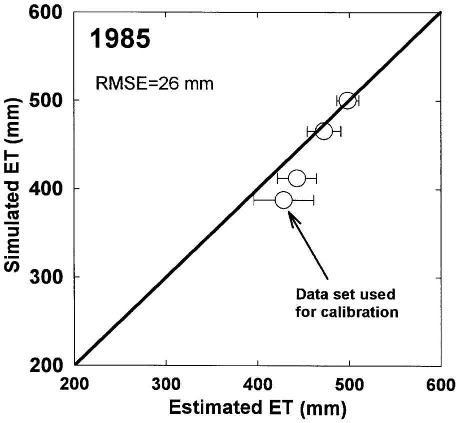

Figure 7. Measured and simulated corn evapotranspiration in 1985 for all four irrigation levels. Vertical bars are one standard deviation around the mean values. See table 2 for corresponding irrigation amounts of each level.

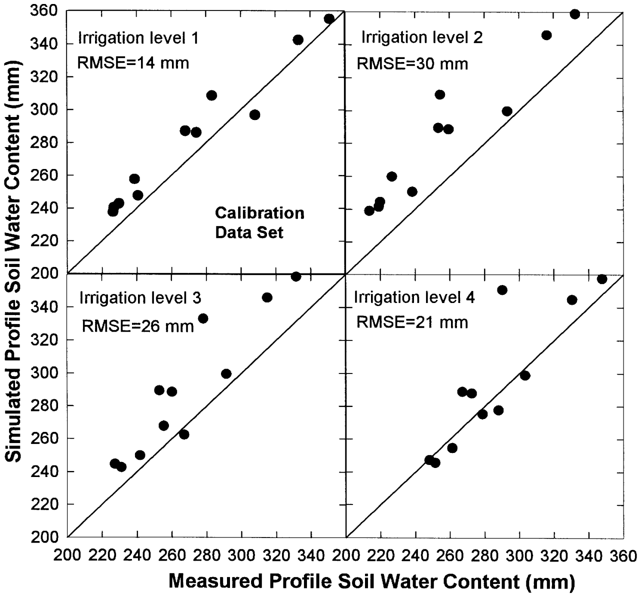

Figure 8. Measured and simulated soil water storage in the 1.80 m soil profile during the 1985 corn growing season.

Model Validation Results

The calibrated model was used to predict crop production for the other three irrigation levels in 1985 and for the three irrigation levels in 1984 and the four irrigation levels in 1986. Leaf area index was adequately predicted at the other three irrigation levels in 1985, with RMSE ranging from 0.22 to 0.33 m^2 m^{-2} (fig. 4), and simulation results did not differ with irrigation level. This is because most of the irrigations were applied after silking, when all of the leaf area development had occurred. The leaf area index simulations in 1984 were overestimated by RZWQM for all three irrigation levels after DOY 210 during the leaf senescence stage, with RMSE ranging from 1.08 to 1.58 m^2 m^{-2}. Plant height was adequately predicted within the experimental variability throughout the growing seasons for all irrigation levels in 1985, with RMSE ranging from 0.15 to 0.17 m (fig. 5). However, plant height was under–predicted during early growth stage in both 1984 and 1986, with a small overestimation of plant height for irrigation levels 1 and 2 in 1984. RMSE ranged from 0.13 m in 1986 to 0.32 in 1984.

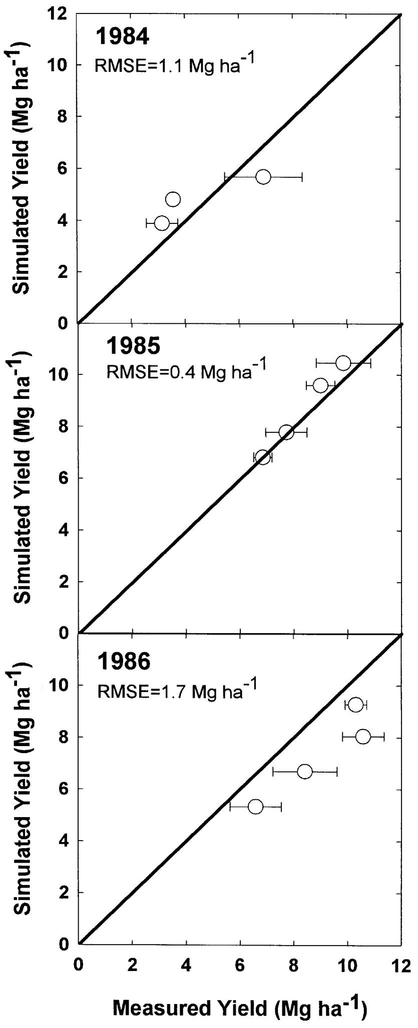

Figure 9. Measured and simulated corn yields in 1984, 1985, and 1986. Vertical bars represent one standard deviation around the mean values.

For the three higher irrigation levels in 1985, RZWQM simulated the increase in aboveground biomass with time well until the final measurement (fig. 6). The final measurement of biomass was overestimated by 14% for irrigation level 2, by 38% for irrigation level 3, and by 33% for irrigation level 4. Biomass simulations during the middle of the 1984 growing season were higher than measured for all irrigation levels, but final biomass predictions were very close to measured biomass for all three irrigation levels. Overall RMSE ranged from 1.2 to 1.9 Mg ha^{-1} in 1984 and from 0.8 to 1.9 Mg ha^{-1} in 1985. In addition, the model reproduced the differences in biomass between 1984 and 1985 caused by different weather conditions and irrigation amounts.

Evapotranspiration (ET) in 1985 (fig. 7) was well simulated in RZWQM using the Shuttleworth–Wallace model for all irrigation levels, with a maximum difference for irrigation level 1 and RMSE of 26 mm. However, this difference is well within the error of estimated ET from soil moisture measurement. The model reproduced the differences in ET due to irrigation levels well. Simulated profile soil water storage for the other three irrigation levels in 1985 correlated well with estimated soil water storage (fig. 8) with somewhat over–prediction by RZWQM for both irrigation levels 2 and 3, but for irrigation level 4 simulated values were close to measured values at all but one sampling time. Perhaps there was a measurement error on that particular date. RMSE for soil water storage ranged from 14 to 30 mm over the 1.80–m soil profile.

Grain yield was adequately predicted by RZWQM for all irrigation levels in 1985, with RMSE of 0.4 Mg ha^{-1} (fig. 9). Under the 1984 conditions, RZWQM overestimated yield by 23% for irrigation level 1, overestimated yield by 35% for irrigation level 2, and underestimated yield by 18% for irrigation level 3. Yields simulated with the 1986 growing season conditions were underestimated by RZWQM for all irrigation levels, with the underestimation ranging from 10% to 24% of measured values. Considering many unknowns and complexity of the yield process, the model results are quite good (fig. 9). These results are comparable to or better than other commonly used models (Ma et al., 2002). However, in a relative sense, the model does respond to different irrigation levels and the impacts of varying weather conditions from year to year.

As stated earlier, RZWQM does not have a detailed phenology model, but it is able to simulate plant development through several discrete life history classes. Observed silking dates were DOY 219 in 1984, DOY 207 in 1985, and DOY 203 in 1986. RZWQM simulated 12%, 16%, and 12% of the plant population in reproductive development on those days in 1984, 1985, and 1986, respectively.

DISCUSSION

The results of evaluating RZWQM for water stress show that RZWQM can be calibrated well for a given irrigation level (e.g., irrigation level 1 in 1985), but the prediction capability of RZWQM for other treatments and years varies. The model predicted grain yield well for all irrigation levels in 1985. Although yield predictions in 1986 were lower than measured values, the calibrated model predicted adequately the relative increase in yield with irrigation water (a measured yield increase of 3.7 Mg ha^{-1} between irrigation level 1 and 4 vs. 3.9 Mg ha^{-1} predicted), which is very important for using RZWQM as a tool to simulate crop yield under different irrigation management.

The model under–predicted leaf senescence in 1984 and should be modified on the projected senescence rate. In addition, the model over–predicted maximum LAI in 1984. In RZWQM, LAI is calculated from leaf biomass and a coefficient to convert leaf biomass to leaf area index (CONVLA). In reality, CONVLA may be affected by water stress. Aboveground biomass was over–predicted during the middle part of the growing season. Thus, further improvement in partitioning of photosynthate between the root and shoot is needed under various stress conditions. Plant height in general was correctly predicted by RZWQM in the calibration year (1985) and over–predicted during the middle and near end of the growing season in 1984 and 1986. Since plant height was scaled between zero and a predefined maximum height according to aboveground biomass at half and full heights, over predictions of aboveground biomass may partially contribute to the higher plant height predictions. New correlations between aboveground biomass and height or phenology should be investigated.

Testing of RZWQM for the three years of data and multiple irrigation treatments demonstrated the importance of good and comprehensive data sets for model validation. For example, based on simulation results of 1985, RZWQM was very good in predicting corn yield, LAI, and aboveground biomass, and reasonably good at predicting soil water content and evapotranspiration. However, since LAI was measured only for the first part of the growing season and not during the senescence phase in 1985, tests of RZWQM for LAI prediction were less rigorous when using data from 1985 than when using data from 1984. Similarly, plant height was reasonably predicted for 1985 and 1986, but not for 1984. Therefore, if we had data only for 1985 to test RZWQM, we would not be able to identify possible discrepancies in LAI, height, biomass, and yield predictions.

As described early, RZWQM assumes a linear relationship between the water stress factor and its impact on biological processes, which may not always be true. For example, many studies (e.g., Denmead and Shaw, 1960; Claasen and Shaw, 1970; Sudar et al., 1981) have shown much larger effects on yield when water stress occurs during reproductive and grain–filling stages than during vegetative development. Compared with the study of Martin and Watts (1999), we did not simulate plant N stress. We found that simulated plant responses to irrigation water were slightly reduced when N stress was simulated simultaneously with water stress. Therefore, some improvements are needed to address water stress and its interaction with N stress. Because considerable changes have been made to RZWQM since Martin and Watts (1999) used RZWQM, efforts are underway to reexamine their now more complete data set.

As shown in this study, goodness of prediction was not the same for yield, biomass, LAI, plant height, and soil water content. Therefore, it is important to have a complete data set for model testing and validation, so that the model is not bias evaluated. For our study, we used the most complete data sets in 1985 for model calibration; unfortunately, less complete data sets were collected in 1984 and 1986 for model validation. Therefore, not all the model outputs can be validated in 1984 and 1986. However, we did have data on corn yield and plant height in all the years, which were used for model validation purposes. Since we used only one irrigation treatment for model calibration in 1985, the RZWQM was also validated on the other three irrigation levels in 1985 with more complete data collected. Therefore, the model evaluation procedure and results in this study are valid. However, model users should be aware of the differences in model predictions among yield, biomass, LAI, height, and soil water content and make appropriate interpretation and extrapolation of model simulation results.

In conclusion, this study demonstrated an application of RZWQM in simulating corn growth under different irrigation levels. Similar to experimental observations, the model did not show differences in LAI, biomass, and plant height among irrigation levels, but the model did show their responses to weather variability from year to year. The model also correctly simulated responses of yield to both irrigation treatments and weather variability from year to year. Simulated crop water use in terms of ET responded well to irrigation amount. Although further improvements are needed, these results show that RZWQM can be used as a tool to simulate plant growth and as a guide for irrigation water management.

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