

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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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.

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),

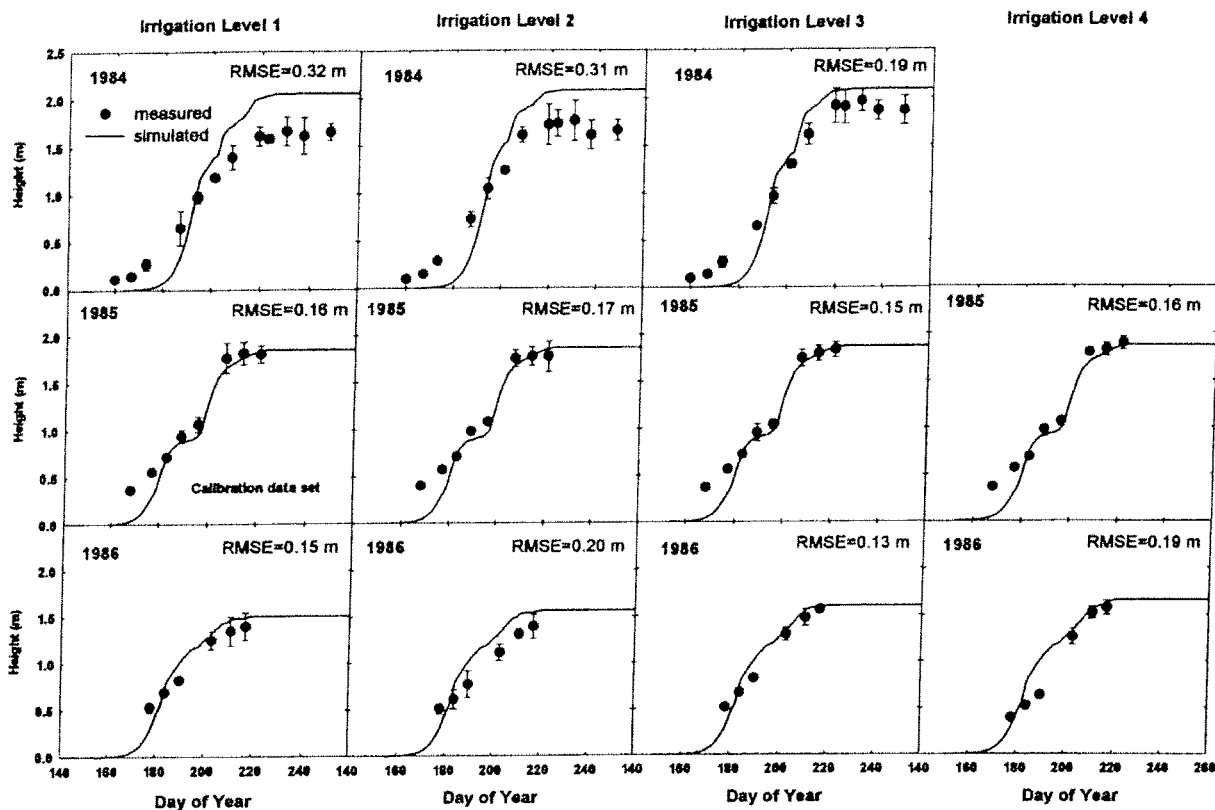


Figure 5. Measured and simulated corn height in 1984, 1985, and 1986. Vertical bars are one standard deviation around the mean values. See table 2 for corresponding irrigation amounts at each level.

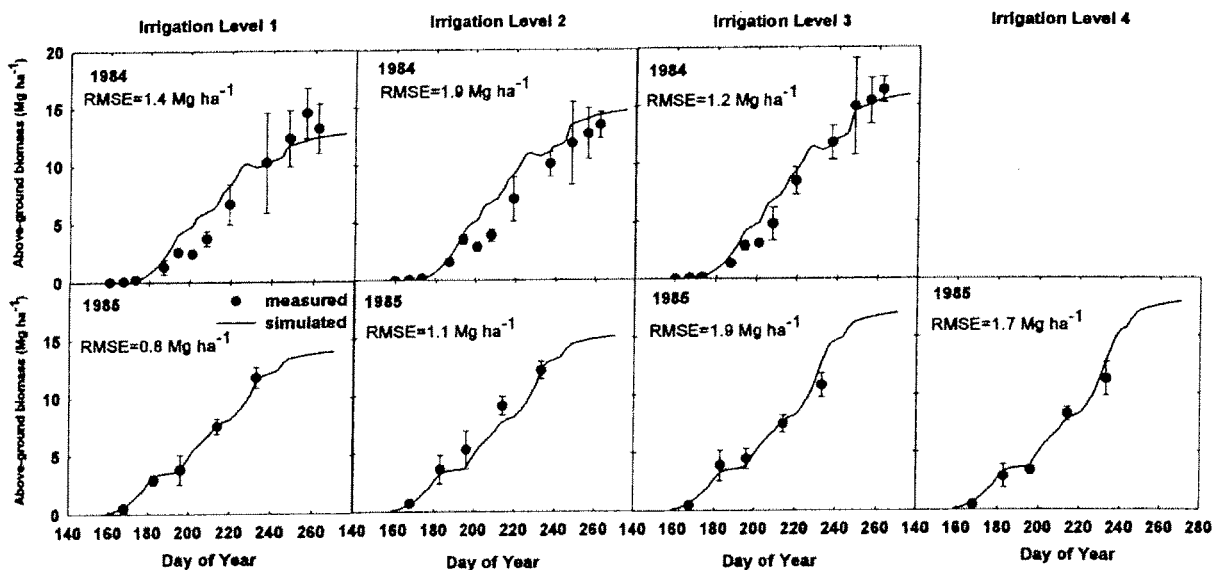


Figure 6. Estimated (from soil water balance) and simulated above-ground corn biomass in 1984 and 1985. Vertical bars are one standard deviation around the mean values. See table 2 for corresponding irrigation amounts at each level.

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.

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 predic-

tions. 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

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