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AGRONOMIC MODELING

Modeling Nitrogen Management Effects on Winter Wheat Production Using RZWQM and CERES-Wheat

S. A. Saseendran, D. C. Nielsen, L. Ma,* L. R. Ahuja, and A. D. Halvorson

ABSTRACT

Agricultural system models can provide an alternative, less time-consuming and inexpensive means of determining the optimum crop N requirement under varied soil and climatic conditions. In this context, we parameterized the Root Zone Water Quality Model (RZWQM) for winter wheat (*Triticum aestivum* L.) production and then evaluated it along with the CERES-Wheat model to assess their potential as N management tools at Akron, Co. Both models were evaluated with data from five N treatments (0, 28, 56, 84, and 112 kg N ha^{-1}) and three crop seasons (1987–1988, 1988–1989, and 1989–1990). Data from 1987–1988 zero-N treatment were used for model calibration, and the rest of the data were used for model validation. Genetic coefficients for winter wheat (cv. TAM 107) were developed for the CERES-Wheat model. The crop parameters required for the generic crop model of RZWQM were parameterized using information from the literature or by calibration. Both models were calibrated first for soil moisture and then for biomass and grain yield. Grain yield predictions had a root mean square error (RMSE) of 500 and 363 kg ha^{-1}, respectively, for CERES-Wheat and RZWQM. Aboveground biomass was predicted with RMSEs of 1247 and 1441 kg ha^{-1}, respectively. Long-term simulations of both RZWQM and CERES for winter wheat growth using historical weather data (1912–2001) showed that 56 kg ha^{-1} N applied as broadcast incorporated is a viable N management option in eastern Colorado, taking into account the grain yield, crop N uptake, N leaching into groundwater, and residual soil N at harvest. Model simulations also showed that the wheat–fallow cropping system is less water use efficient than a continuous wheat system under rainfed agriculture in eastern Colorado.

If water is abundant, crop growth and yield greatly depend on soil N supply. With evolution of high-yielding varieties, N demand in agriculture is ever increasing. With little information on the amount of N required for cropping practices on different soils, farmers generally apply as much fertilizer as resources permit to increase yield. Consequently, the excess N left in the soil finds its way into the atmosphere and surface and ground water bodies through various chemical and physical processes, leading to environmental pollution. Enhanced aboveground biomass growth stimulated by excessive N availability in the soil can result in higher transpiration rates, less available soil water during flowering and grain filling, and less grain yield in winter wheat (Ritchie and Johnson, 1990; Nielsen and Halvorson, 1991). Under rainfed agriculture, lack of water in the root zone can make the applied N unavailable to plants and subject to leaching or runoff later. Hence, proper management of N is the key for a better environment and improved crop production. Therefore, there is a need for a more demand-based application of N fertilizer depending on the absorption capacity of the soil and plant in light of the climatic and soil physicochemical conditions.

Field experiments for quantifying optimal crop N requirement are time consuming, requiring many years of trials at multiple locations. Experimental results are used to develop general fertilizer recommendations for the whole region although experiments are conducted on a small scale. These recommendations consequently cannot take into account factors like soil and weather variability across locations (Mathews and Blackmore, 1997). As N movement in soil is controlled by soil water, this problem becomes more severe under rainfed agricultural practices, than when irrigated, in the semiarid climates characterized by high rainfall variability and frequent soil moisture deficiencies. Under these situations, crop simulation models can help synthesize much of the information accumulated from the various experiments at diverse locations and can provide a way of extrapolating this information to other regions of interest, with different soil–climatic characteristics (Mathews and Blackmore, 1997). Simulation of various crop and fertilizer management strategies using such models can lead to better fertilizer decision-making (Godwin and Jones, 1991; Paz et al., 1998, 1999).

RZWQM is a process-oriented model designed to predict the hydrologic, chemical, and biological responses to agricultural management practices (Hanson et al., 1998; Ahuja et al., 2000a). The OMNI model drives the organic matter/N cycling in RZWQM (Shaffer et al., 2000). RZWQM has a generic crop model (Hanson, 2000) that can be parameterized to simulate a specific annual crop. The plant model simulates both plant population development and plant growth. Population dynamics are simulated using a modified Leslie matrix model (Ahuja et al., 2000b). Phenological development, while not explicitly simulated, predicts seven growth stages (Hanson, 2000). This is achieved through the specification of optimum development rates for dif-

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Abbreviations: CW, continuous wheat; ET, evapotranspiration; NOF, normalized objective function; NUE, nitrogen use efficiency; RMSE, root mean square error; W-F, winter wheat–fallow; WUE, water use efficiency.

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ferent growth stages in terms of calendar days and reduced in proportion to the current environmental stresses (water, N, and temperature). Growth stages simulated are (i) dormant seeds, (ii) germinating seeds, (iii) emerged plants, (iv) established plants, (v) plants in vegetative growth, (vi) reproductive plants, and (vii) senescent plants. Detailed descriptions of the different components of RZWQM are available elsewhere (Ahuja et al., 2000b; Hanson et al., 1998).

The generic crop model of RZWQM has already been parameterized to simulate corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] and validated against measured data in various States in the USA (Hanson et al., 1999; Wu et al., 1999; Ghidey et al., 1999; Jaynes and Miller, 1999; Martin and Watts, 1999; Farahani et al., 1999; Landa et al., 1999). Major components of RZWQM have been validated by Ma et al. (2001). The generic crop model of RZWQM has not been parameterized and assessed for winter wheat production. It remains to be evaluated for its potential use in optimizing N management practices for both yield and quality of environment.

The CERES-Wheat model (Ritchie et al., 1988; Godwin et al., 1989; Singh et al., 1991) also simulates crop growth and development and is available to users as part of the DSSAT 3.5 (Decision Support System for Agrotechnology Transfer) suite of crop models designed to estimate production, resource use, and risks associated with crop production practices (Tsuji et al., 1994; Jones et al., 1998). The CERES-Wheat model simulates phenological development of the crop; growth of grains, leaves, stems, and roots; biomass accumulation based on light interception and environmental stresses; soil water balance; and soil N transformations and uptake by the crop. The N module in DSSAT is based on the approaches described by Seligman and van Kuelen (1981) in PAPRAN model for pasture growth in response to soil water and N. Godwin and Singh (1998) have modified or replaced several important components. A complete description of the CERES–Wheat model is published elsewhere (Ritchie et al., 1998). Kovács et al. (1995) reported satisfactory results in studies to evaluate the capacity of the CERES-Wheat model as a tool to simulate grain yields, N uptake, and nitrate accumulation in the soil through many years of variable weather and soil conditions in Hungary. Bowen and Papajorgji (1992) reported satisfactory simulations of the effect of N fertilizer on winter wheat yields in Albania. Timsina et al. (1998) used CERES-Wheat and rice (*Oryza sativa* L.) models for modeling the cultivar, N, and moisture effects on a rice–wheat sequence cropping system in Bangladesh.

There are considerable differences in the way different physical processes of the water balance components of the two models are simulated. In RZWQM, overwinter simulations make use of snowmelt routines patterned after PRMS (Precipitation Runoff Modeling System) (Flerchinger et al., 2000). In CERES, there is no overwinter snowmelt simulation. In RZWQM, infiltration of rain or irrigation water is simulated by Green–Ampt equation (Green and Ampt, 1911), and subsequent water redistribution is calculated by solving the Richard's equation. Soil hydraulic properties are estimated using the Brooks–Corey equation (Brooks and Corey, 1964). Evapotranspiration (ET) is estimated from a soil–canopy–residue system using a revised form of the Shuttleworth and Wallace (1985) double-layer model (Farahani and Ahuja, 1996). Additionally, processes like preferential flow of soil water through macropores and effect of tillage and crop residue on soil hydraulic properties are simulated (Ahuja et al., 2000b). Also, in RZWQM, up to 50% of the aboveground biomass can senesce due to water and freezing stress and tissue aging. Dead aboveground biomass as well as dead root biomass are continuously sloughed into the soil organic pools, affecting the soil physical and hydraulic properties (Hanson, 2000). In CERES-Wheat, the four most recently developed leaves are maintained green while others senesce. The philosophy behind the water balance in CERES-Wheat is to use minimum data that are widely available to calculate water stress–related yield reductions in crop simulations (Ritchie, 1998); hence, only minimum processes are simulated following a layered soil and a tipping-bucket approach. Runoff and infiltration are simulated using the USDA curve number technique (Williams, 1991). Evapotranspiration calculations are based on the Ritchie (1972) adaptation of Priestley–Taylor approach (Priestley and Taylor, 1972). This method avoids the use of wind and vapor pressure data that are not widely available for potential ET calculations. Also there is considerable difference in the modeled interactions between water balance and other components. For example, in CERES–Wheat, crop development rates are calculated based only on temperature and photoperiod (Ritchie et al., 1998), whereas in RZWQM, the growth stages discussed above are modified by an environmental fitness factor based on the current temperature, N, and water stresses (Hanson, 2000). Soil organic matter in RZWQM is distributed over five computational pools and is decomposed by three types of microbial populations, and soil organic matter in CERES-Wheat consists of a fast-decaying *fresh organic matter* and a *soil humus fraction* that is slowly decaying. Volatilization loss of N is not simulated for dryland conditions in CERES-Wheat, however (Godwin and Singh, 1998).

Procedures for simulations of plant N uptake by the two models also differ greatly. In RZWQM, plant transpiration drives the passive uptake of N into the plant. Soil water and N are extracted by layer in proportion to the root biomass present and amount of N in the soil water. If passive uptake fails to supply the N demands, active uptake occurs using a process similar to the Michaelis–Menten substrate model if more N is available in the soil (Hanson, 2000). In CERES-Wheat, N uptake is simulated based on the crop N demand and potential N uptake rate as described by Godwin and Singh (1998).

Specific objectives of the present study were to (i) evaluate and apply RZWQM and CERES-Wheat models for simulating effects of different N management practices on grain yield, crop N uptake, N leaching, and soil residual N at harvest and (ii) simulate crop rotation effects on N and water use efficiency (WUE) in continuous wheat (CW) and wheat–fallow (W-F) under no-till rainfed systems in the semiarid climate of eastern Colorado.

MATERIALS AND METHODS

Field Experiment

Winter wheat growth and development data were collected at the Central Great Plains Research Station (40°9′ N, 103°9′ W; 1384 m above mean sea level), 6.4 km east of Akron (eastern Colorado), during the crop seasons of 1987–1988, 1988–1989, and 1989–1990. These data were described in part by Nielsen and Halvorson (1991). Winter wheat (cv. TAM 107) was planted on 14 Sept. 1987, 24 Sept. 1988, and 18 Sept. 1989. A randomized complete block experimental design was used, with four replications at five N treatment levels of 0, 28, 56, 84, and 112 kg N ha^{-1} broadcast as ammonium nitrate just before planting. No-till winter wheat was grown on plots 9.1 by 12.2 m that had previously been in a 12-mo no-till chemical fallow period with corn residue. The plots used for wheat planting were different for different years. The soil was a Platner loam (fine, montmorillonitic, mesic Aridic Paleustoll). Soil water at depths of 0 to 30, 30 to 60, 60 to 90, 90 to 120, 120 to 150, and 150 to 180 cm at the center of each plot were measured weekly using a neutron probe from early April until grain harvest. Measured soil water data were used to calculate ET by the water balance method (Rosenberg et al., 1983). Runoff and deep percolation were assumed to be negligible under these rainfed, no-till conditions. Grain yield, aboveground biomass, and soil moisture were measured in all 3 yr and for all of the N treatments. Both models were calibrated for 0 kg N ha^{-1} treatment in the crop year of 1987–1988, and rest of the experiments were utilized for validation of the model performance.

Daily rainfall, maximum and minimum air temperature, solar radiation, wind speed, and relative humidity were recorded at the research station. As there were no hourly observations of rainfall collected during the experimental period, in the model simulations, we assumed that the daily rainfall records were made up of single storms of 2-h durations. This was done based on the fact that there was no appreciable amount of runoff observed in the field, and the model simulations with the assumption of a 2-h storm were found to be adequate for producing minimum runoff under Colorado conditions (Ma et al., 1998). Soil data for Platner loam soil were collected from the Soil Characterization Pedon Database of USDA-NRCS (www.nrcs.usda.gov; verified 2 Feb. 2004). For the long-term model simulations, the historical daily weather data of rainfall, maximum and minimum temperature, and solar radiation collected at the Central Great Plains Research Station during the period 1912–2001 were utilized. To come up with the best N management strategy considering the risks associated with production due to weather variability of the location, the crop model is set up with seasonal strategies in terms of crop variety, planting dates, N application rates, etc., and simulated across the historical observed weather data (1912–2001). The simulation results can then be analyzed to come up with the best management strategy for the location in terms of economic yield return. As such, in this study, all of the long-term simulations, with the exception of crop rotation runs, of both the models were run from 1 Jan of every year, with the same initial soil moisture and N conditions to study N management effects due only to weather variability. There was no carryover of soil properties from one season to the other. The same procedure was adopted for the calibration and validation studies as well. In the crop rotation studies, both models were run continuously from 1 Jan. 1912 through 31 Dec. 2001, and all of the soil properties were carried over from one crop year to the other. Solar radiation and wind speed data were available only from the year 1983 through 2001. The solar radiation and wind speed data records were extended backward to 1912 using the CLIGEN90 weather generator utility available in the RZWQM (Hansen et al., 1994).

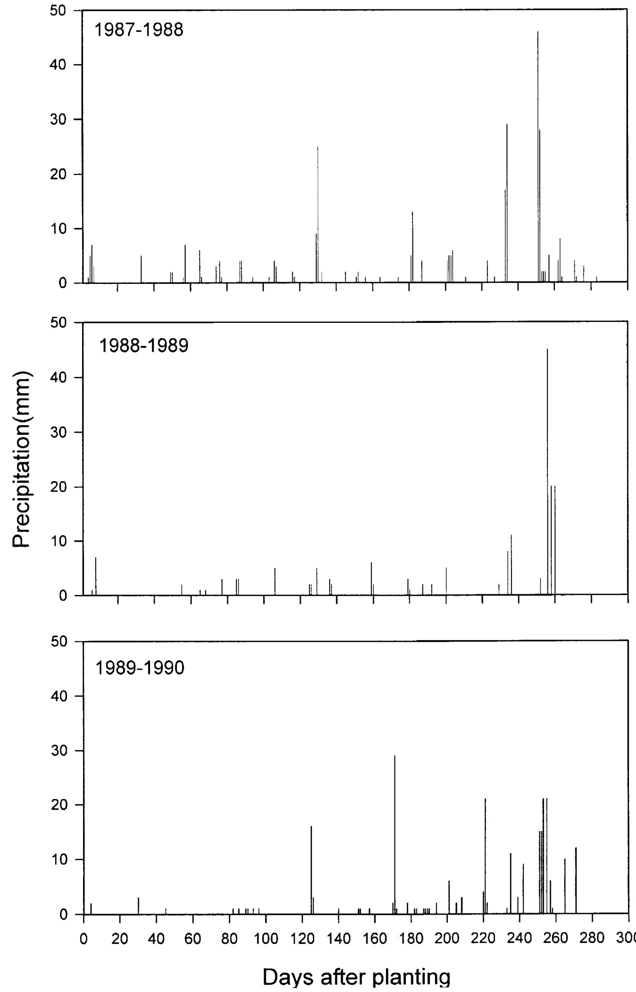

Fig. 1. Daily precipitation recorded at Akron during winter wheat crop seasons of 1987–1988, 1988–1989, and 1989–1990.

Mean annual precipitation at the study site was 41 cm (1960–1990), and during the winter wheat growing season (September through July), mean was 36 cm. There was high variability in the amount and temporal distribution of precipitation at the site across the three crop seasons (Fig. 1). The 1987–1988 crop received 35 cm of precipitation (near average). Crop seasons of 1988–1989 and 1989–1990 received 19 and 24 cm of precipitation, respectively. The 1988–1989 crop season was the driest, receiving only about 52% of the long-term mean, but its temporal distribution was comparable to the other 2 yr.

RESULTS AND DISCUSSION

Calibration of RZWQM

Process-oriented models like RZWQM require detailed information of the system (Hanson et al., 1999; Ahuja and Ma, 2002). The model developers recom-

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Table 1. Calibrated soil moisture constants for RZWQM and CERES-Wheat models.

	CERES		RZWQM	Values reported in NRCS database	
Soil layer depth	Lower limit of water content	Drained upper limit of water content	33 kPa water content	1500 kPa water content	33 kPa water content
cm	$cm^3\ cm^{-3}$				
0–5	0.100	0.243	0.400	0.15	0.32
5–15	0.100	0.243	0.400	0.15	0.32
15–30	0.101	0.246	0.400	0.15	0.32
30–45	0.105	0.243	0.400	0.22	0.40
45–60	0.100	0.248	0.393	0.17	0.34
60–90	0.100	0.240	0.383	0.09	0.22
90–120	0.101	0.246	0.383	0.09	0.22
120–150	0.102	0.244	0.380	0.09	0.22
150–178	0.101	0.244	0.380	0.09	0.22

mend that users calibrate the soil water content, then the N component, and finally the plant production component of RZWQM (Ma et al., 2003). Detailed procedures for calibrating RZWQM as followed in this study were laid out by Hanson et al. (1999) and Ahuja and Ma (2002). A normalized objective function (NOF) for quantifying the goodness of a model parameterization as suggested by Ahuja and Ma (2002) was used. The NOF was calculated as:

$$\mathrm{NOF} = \mathrm{RMSE}/O_{\mathrm{avg}} \quad [1]$$

where RMSE is root mean square error and O_{avg} is average of measured values. A perfect match of measured and predicted values results in NOF = 0.

Data from 0 kg N ha^{-1} treatment of 1987–1988 crop season were used in both RZWQM and CERES-Wheat model calibrations, and both models were run from first of January of the year in which the crop was planted. The three crop years were simulated separately. After specifying all input requirements of the model, following the calibration procedure for soil moisture as laid out by Hanson et al. (1999) and Ahuja and Ma (2002), an NOF of soil moisture of 0.20 was obtained. To improve simulation of soil moisture for RZWQM, we calibrated the 33 kPa soil water content values by varying their values for each soil layer within the highest (0.4 cm^3 cm^{-3}) and lowest (0.22 cm^3 cm^{-3}) values of 33 kPa soil water contents as reported for Platner loam soil in the Soil Characterization Pedon Database of USDA-NRCS (www.nrcs.usda.gov) (see Table 1).

The soil N component of RZWQM was calibrated next. This involves establishment of initial soil C/N ratio pool sizes for fast and slow residue pools; slow, medium, and fast soil humus pools; and the three microbial pools (aerobic heterotrophs, autotrophs, and facultative heterotrophs) (Hanson et al., 1999). No laboratory procedures were known to effectively determine the sizes of these pools (Ahuja and Ma, 2002). Hence, as recommended by Ahuja and Ma (2002), we started with a first guess for the three humus organic matter pool sizes of 5, 10, and 85%, respectively, for fast, medium, and slow pools and set the microbial pools at a minimum level of 50 000, 500, and 5000 organisms g^{-1} soil, respectively, for aerobic heterotrophs, autotrophs, and facultative heterotrophs. Because previous management at a site determines the initial state of a soil in terms of its organic matter and microbial populations, running a model with previous management before the experiment setup will create a better initial condition for these parameters (Ma et al., 1998). Hanson et al. (1999) suggested 5- to 7-yr runs for short-term stability of the soil organic matter pool sizes and 20 or more years for long-term stability. Thus, we have run the model for 21 yr for stabilizing the soil organic matter pools.

Finally, the generic crop growth model was calibrated. To facilitate calibration of the generic crop model of RZWQM, the plant parameters were divided into groups of *species-specific parameters* and *regional parameters* (Hanson and Hodges, 1992). The set of 86 parameters of the first group was set by the model developers and held constant for each crop species, as recommended. The latter group of five parameters (Table 2) was set to capture region- or location-specific differences in crop performance. As RZWQM model was not parameterized earlier for wheat, both sets of parameters need to be determined in present study. Procedures and methods for calibrating these parameters were described elsewhere (Hanson et al., 1999; Ahuja and Ma, 2002). Values of the five regional parameters arrived at for winter wheat at Akron are shown in Table 2. Since RZWQM does not simulate tillers, we used the final plant population as seed population at planting.

Parameterization of species-specific parameters needed data from specific experiments. There were six important species-specific parameters for RZWQM, and their values were derived from the literature (Table 3). Remaining parameters were calibrated based on trial and error from model runs. To facilitate trial-and-error estimation, a computer program was used to run the model with input estimates of these parameters over a range of values, based on literature and default values available in the RZWQM model. Combination of genetic

Table 2. List of five regional parameters used by generic crop model of RZWQM and their estimates for winter wheat cultivar TAM 107 at Akron, CO.

Parameter	Values
1. Maximum active N uptake, g $plant^{-1}$ d^{-1}	1.40
2. Daily respiration as a function of photosynthate, fraction	0.250
3. Biomass to leaf area conversion coefficient, g LA^{-1}	0.33
4. Age effect for plants in the propagules development stage, fraction	0.95
5. Age effect for plants in the seed development stage, fraction	0.92

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Table 3. Crop-specific parameters used for calibrating generic plant growth model of RZWQM model for winter wheat simulation at Akron.

Parameter	Value	Reference
1. Light use efficiency coefficient, mol CO_2 mol^{-1} PAR†	0.08	Tubiello et al. (1995)
2. Theoretical maximum photosynthetic rate, μmol CO_2 m^{-2} s^{-1}	23.0	Teramura et al. (1990); Boote and Loomis (1991)
3. Canopy light extinction coefficient	0.85	Porter and Gawith (1999)
4. Maximum temperature for plant growth, °C	37.5	Porter and Gawith (1999)
5. Minimum temperature for plant growth, °C	0.0	Porter and Gawith (1999)
6. Optimum temperature for plant growth, °C	20.0	Al-Khatib and Paulsen (1984)

† PAR, photosynthetically active radiation.

parameters with the lowest NOF value was selected (Table 4). The above procedure was iterated a few times.

Calibrated soil water contents are given in Table 1, and the NOF value of soil moisture simulation is 0.097 (Table 5). A comparison of field-measured and model-simulated soil water content with time in different soil layers is presented in Fig. 2. The RMSE of predicted soil water contents by RZWQM was 0.023 cm^3 cm^{-3} (Table 5). Agreement between measured and predicted soil water in the first two soil layers (60 cm) was less compared with the deeper layers, but the deviations were generally within one standard deviation of measured mean values. High standard deviations (error bars in Fig. 2) in measured soil water content showed the high spatial variability in soil moisture under rainfed conditions in the field. The error in soil water simulation by the model was mainly due to errors in ET simulations (Table 6). During calibration period, the model underpredicted cumulative ET by 32%. In addition, we used multiobjective parameterization scheme that optimized crop yield, biomass, and soil water contents. The calibrated grain yield has an accuracy of about –2% (Fig. 3) deviation from measured value, and total aboveground biomass has an accuracy of about 7% (Fig. 4).

Calibration of CERES-Wheat

In the present study, we had information on (i) anthesis date, (ii) maturity date, (iii) grain yield, and (iv) biomass at maturity. Godwin et al. (1989) suggested an iterative approach to reach reasonable estimates of the coefficients through trial-and-error adjustments to match the observed phenology and yield with those simulated by the model, if the data for calibration of the genetic

Table 4. Calibrated species-specific parameters for winter wheat simulation using RZWQM.

Parameters	Value
1. Stem diameter of the mature plant cylinder, cm	30
2. Stem height of the mature plant cylinder, cm	100
3. Aboveground biomass at which height is one-half maximum height, g	20
4. Aboveground biomass of a mature plant, g	25
5. Aboveground biomass of plant at four-leaf stage, g	7.5
6. Maximum whole-plant N content, proportion	0.060
7. N content when plant is at Growth Stage 1.0, proportion	0.050
8. Minimum shoot N needed for plant growth, proportion	0.004
9. N uptake efficiency coefficient, mg kg^{-1}	0.500
10. Minimum N content for leaves, proportion	0.010
11. Maximum N content for leaves, proportion	0.020
12. Minimum N content for stems, proportion	0.010
13. Maximum N content for stems, proportion	0.030
14. Minimum N content for roots, proportion	0.010
15. Minimum N content for propagules, proportion	0.005
16. Maximum N content for seeds, proportion	0.060
17. Leaf water tension at which plant growth activity is half maximum, cm H_2O	−9 000
18. Q10 value for respiration	2
19. Respiration coefficient	0.01
20. Maximum root/shoot ratio	0.80
21. Minimum root/shoot ratio	0.20
22. Leaves/shoot ratio	6.50
23. Maximum leaf area, cm^2	7.00
24. Biomass of a seed, g/plant	0.002
25. Total maintenance requirements as proportion of photosynthate	0.150
26. Maintenance requirements for roots as proportion of photosynthate	0.050
27. Average 10-d temperature that must be met for initial growth, °C	5.000
28. Average 5-d soil water head at which germination is one-half, cm H_2O	−12 000
29. Germination rate, no./d	0.15
30. Number of accumulated stress-free days for germination	1.5
31. N content in leaves at germination, proportion	0.02
32. N content in stems at germination, proportion	0.02
33. Percentage postsenescence-induced shoot death proportion	0.009
34. Proportion of water stress–induced death	0.001
35. Temperature at which the plant freezes, °C	−29.00
36. Proportion of photosynthate to propagules	0.60
37. Proportion of propagule to seeds/d	0.13
38. Time needed for plant to germinate, d	3
39. Time needed for plant to emerge, d	12
40. Time needed for plant to grow to four-leaf stage, d	15
41. Time needed for plant to complete vegetative growth, d	155
42. Time needed for plant to complete reproductive growth, d	40

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Table 5. Performance of RZWQM and CERES-Wheat models in soil moisture predictions under different N treatments. Soil moisture data from all of the soil layers under each treatment were pooled together and treated as a single set for computation of RMSE/normalized objective function (NOF).

Treatment	RMSE ($cm^3\ cm^{-3}$)/NOF of soil moisture	
	RZWQM	CERES
kg N ha^{-1}		
	1987–1988	
0	0.023† (0.097†)‡	0.023† (0.097†)
28	0.023 (0.099)	0.030 (0.132)
56	0.024 (0.102)	0.028 (0.119)
84	0.032 (0.131)	0.030 (0.132)
112	0.033 (0.144)	0.037 (0.160)
Mean	0.027 (0.115)	0.031 (0.128)
	1988–1989	
0	0.023 (0.125)	0.064 (0.229)
28	0.022 (0.126)	0.100 (0.462)
56	0.022 (0.126)	0.052 (0.242)
84	0.022 (0.126)	0.074 (0.344)
112	0.023 (0.125)	0.083 (0.386)
Mean	0.022 (0.126)	0.074 (0.347)
	1989–1990	
0	0.024 (0.113)	0.066 (0.297)
28	0.021 (0.115)	0.056 (0.251)
56	0.019 (0.111)	0.076 (0.341)
84	0.021 (0.116)	0.076 (0.338)
112	0.018 (0.111)	0.088 (0.392)
Mean	0.021 (0.113)	0.071 (0.324)

† Calibration value, hence not included in the average.
‡ Values given in parentheses are NOF values.

coefficients are limited. Following this approach, we developed a computer program to uniformly vary the six genetic coefficients of wheat over the range values (Table 7). The crop was simulated for each combination of coefficients, and the mean NOF of simulated grain yield and biomass was calculated. The combination of genetic parameters that gave minimum error (NOF) was selected.

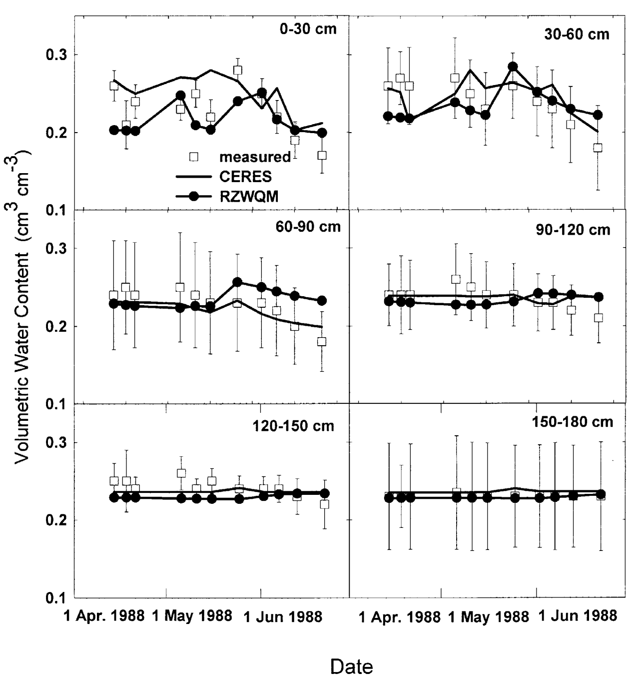

Fig. 2. Comparison of field-measured and CERES-Wheat– and RZWQM-predicted soil water content with time in different soil layers. Error bars represent one standard deviation from mean of measured values.

After initial calibration for genetic coefficients, the soil physical and hydraulic properties were calibrated to improve soil water simulation. In this procedure, we adjusted the soil parameters, namely: (i) albedo, (ii) soil first-stage evaporation limit, (iii) drainage rate, and (iv) root growth factor for different layers of the soil. After obtaining the best possible agreement between measured and predicted soil moisture through trial and error, we proceeded on to calibrating the upper and lower drained limit of soil water contents in each soil layer. Initial drained upper and lower limits for Platner loam soil were obtained from the Soil Characterization Pedon Database of USDA-NRCS (www.nrcs.usda.gov) (Table 1), assuming the upper and lower limits to be the 33 and 1500 kPa soil water contents, respectively. These initial values were then varied between the maximum value of 0.4 $cm^3\ cm^{-3}$ and minimum value of 0.09 $cm^3\ cm^{-3}$ (Table 1). The combination of the upper and lower soil water limits that gave the minimum value of NOF was selected. A comparison of the field-measured and model-simulated soil water content with time in different soil layers is presented in Fig. 2. The RMSE of predicted soil water contents by CERES model was 0.023 $cm^3\ cm^{-3}$ (Table 5). The model overpredicted water content in the top two layers of the soil (Fig. 2). With depth, the difference between predicted and field measured values narrowed down. High standard deviations (error bars in Fig. 2) in measured soil water contents show the high spatial variability in soil moisture under rainfed conditions in the field. Error in soil water simulation by the model was mainly due to the errors in ET simulations (Table 6). The model underpredicted cumulative ET by 39%. Using the newly derived soil parameters, we again recalibrated the genetic coefficients by repeating the procedure described earlier in this section. The final values of genetic parameters for winter wheat (cv. TAM 107) are given in Table 7. Using the calibrated genetic coefficients, a grain yield prediction accuracy of 1.21% (Fig. 3) and a total aboveground biomass prediction accuracy of about −4% (Fig. 4) were obtained.

Validation of RZWQM

RMSE of predicted soil water contents averaged across treatments ranged from 0.021 $cm^3\ cm^{-3}$ for the crop year of 1989–1990 to 0.027 $cm^3\ cm^{-3}$ for 1987–1988 against the calibrated RMSE of 0.023 $cm^3\ cm^{-3}$ for 0 kg N ha^{-1} experiment of 1987–1988 crop season (Table 5). Errors in soil moisture predictions were mainly due to errors in simulations of ET. Averaged across treatments, model-simulated cumulative ETs showed RMSEs of 12.0, 10.7, and 11.2 cm for the crop seasons of 1987–1988, 1988–1989, and 1989–1990, respectively (Table 6).

Grain yield simulation results showed that, RZWQM responds well to N application rates as measured in field experiments (Fig. 3). In the 1987–1988 crop season, predicted grain yields under all N application rates followed the same trend as measured. Grain yield predictions for 28 kg N ha^{-1} treatment in 1988–1989 and for

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Table 6. Water balance components and crop N uptake simulated by CERES and RZWQM models at different N applications.

Year	Crop season total precipitation	Applied N	Cumulative crop ET†			Runoff		Crop N uptake	
			Measured	RZWQM	CERES	RZWQM	CERES	RZWQM	CERES
	cm	kg/ha	cm					kg/ha	
1987–1988	34.6	0	28.5‡	19.2‡	17.3‡	4.57	4.81	147	62
		28	29.9‡	19.3‡	18.2‡	4.57	4.81	169	94
		56	32.8‡	19.6‡	18.0‡	4.57	4.81	184	121
		84	32.7‡	19.7‡	18.1‡	4.57	4.81	185	144
		112	32.9‡	19.5‡	18.1‡	4.57	4.81	203	159
Mean			31.6‡	19.5‡	17.9‡	4.57	4.81	177	116
RMSE				12.0	13.5				
1988–1989	19.0	0	20.2§	12.6§	14.3§	1.31	2.7	98	76
		28	24.1§	12.4§	14.4§	1.31	2.7	107	88
		56	24.1§	12.7§	14.3§	1.31	2.7	175	88
		84	24.1§	12.7§	14.1§	1.31	2.7	159	81
		112	23.8§	12.7§	14.1§	1.31	2.7	132	81
Mean			23.3§	12.6§	14.2§	1.31	2.7	126	83
RMSE				10.7	9.2				
1989–1990	24.0	0	22.4¶	14.8¶	16.9¶	1.54	2.36	81	49
		28	28.2¶	16.4¶	16.7¶	1.54	2.36	102	75
		56	27.6¶	16.3¶	16.7¶	1.54	2.36	130	81
		84	28.6¶	16.4¶	16.8¶	1.54	2.36	144	82
		112	28.8¶	16.3¶	16.8¶	1.54	2.36	160	84
Mean			27.1¶	16.0¶	16.8¶	1.54	2.36	123	74
RMSE				11.2	10.6				

† ET, evapotranspiration.
‡ Duration of cumulative crop ET is from 14 April to 8 July 1988.
§ Duration of cumulative crop ET is from 16 March to 10 July 1989.
¶ Duration of cumulative crop ET is from 2 April to 3 July 1990.

56 and 112 kg N ha^{-1} treatments in 1989–1990 deviated from the measured trend. In all four validation treatments of 1987–1988, grain yield predictions were within ±1 standard deviation of observed variability in the field (Fig. 3). Departure of predictions from observed values were 2, 18, 15, and 7% for the 28, 56, 84, and 112 kg N ha^{-1} experiments, respectively. Grain yields in the crop year of 1988–1989, the driest of the three, were also well predicted by the model, except for the 28 kg ha^{-1} treatment, falling within ±1 standard deviation of the observations (Fig. 3). The deviations of simulations from the observations during this crop season were 2, −23, 0, −13, and 1% for the 0, 28, 56, 84, and 112 kg N ha^{-1} treatments. Model predictions in the crop

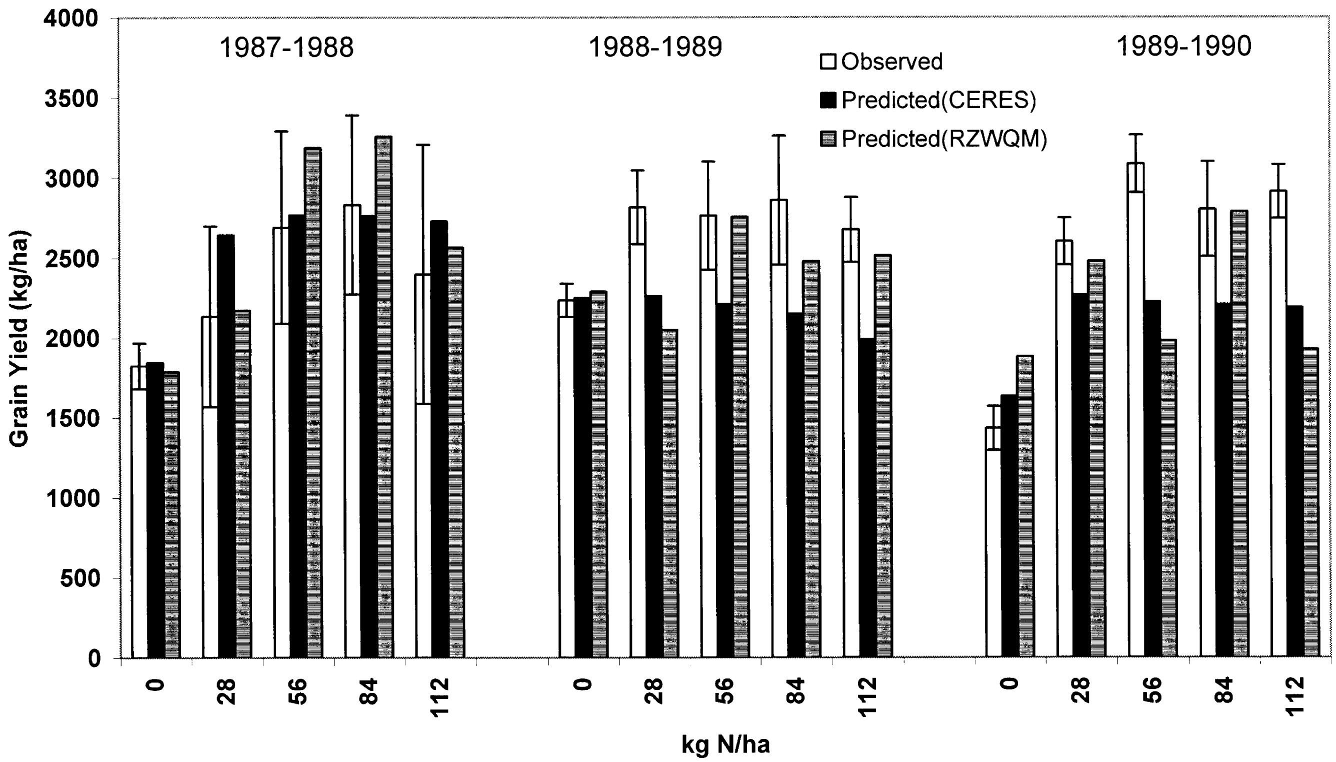

Fig. 3. Measured and CERES-Wheat– and RZWQM-predicted winter wheat grain yields during three crop seasons of 1987–1998, 1988–1989, and 1989–1990 under different N treatments (0 kg N ha^{-1} experiment of 1987–1988 was used for calibration of the models). Error bars represent one standard deviation of measured grain yield from mean.

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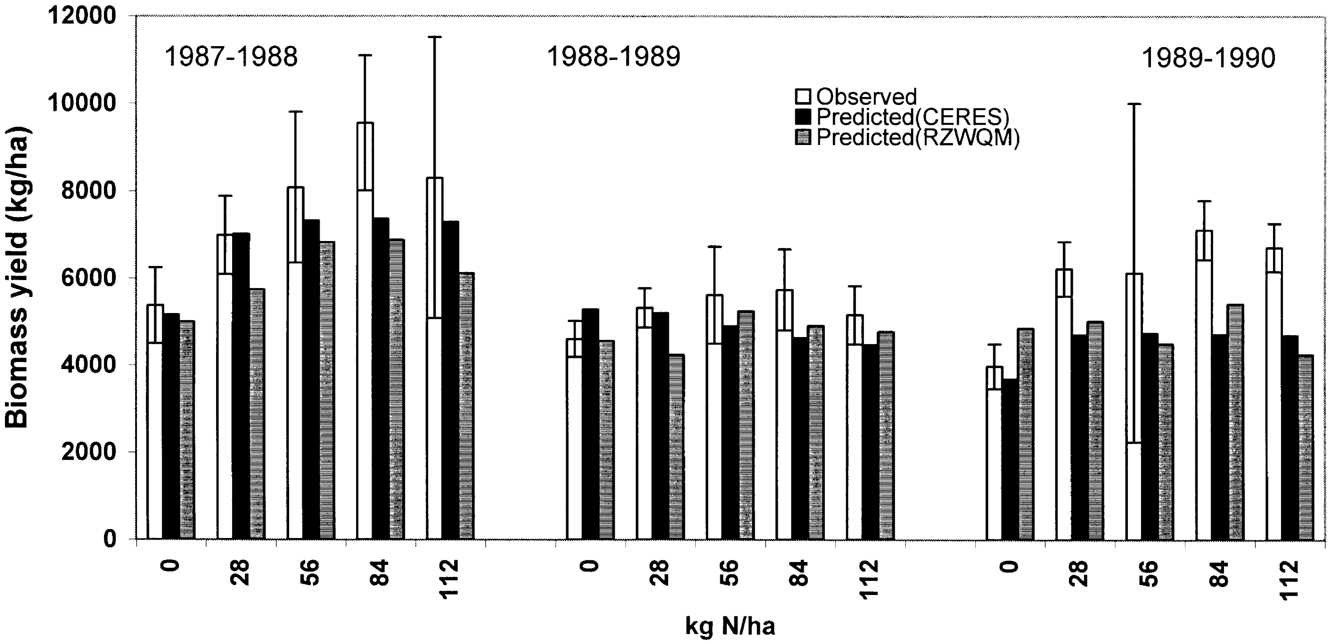

Fig. 4. Measured and CERES-Wheat– and RZWQM-predicted winter wheat biomass during three crop seasons of 1987–1998, 1988–1989, and 1989–1990 under different N treatments (0 kg N ha^{-1} experiment of 1987–1988 was used for calibration of the models). Error bars represent one standard deviation of measured biomass from mean.

year of 1989–1990 were less accurate (Fig. 3). Predictions departed from the observations during this crop year by 31, −6, −36, −1, and −33% for the 0, 28, 56, 84, and 112 kg N ha^{-1} application rates, respectively. Errors in crop yield predictions in this season were due to the interaction between the soil water and N stresses, resulting in a decline in N uptake, averaged across treatments, by 31 and 11% compared with the 1987–1988 and 1988–1989 crop seasons, respectively (Table 6). However, the 31% increase in grain yield under the 0 kg N ha^{-1} treatment could not be explained by this mechanism. Average plant usable N content in the 0- to 180-cm soil profile under 0 kg N ha^{-1} treatment simulated during 1987–1988, 1988–1989, and 1989–1990 crop seasons was comparable at 120, 143, and 110 kg N ha^{-1}, respectively. For the 1989–1990 crop season, averaged across different N treatments, cumulative ET simulations showed a RMSE of 11.2 cm. A RMSE value of 363 kg ha^{-1} was observed in the predictions of grain yields across the five N treatments and three crop seasons.

RZWQM biomass simulation results also showed that it responds well to N application rates as measured in the field experiments (Fig. 4). Model predictions of biomass also followed a similar trend as grain yield discussed above. In general, biomass predictions (Fig. 4) by the model were in better agreement with the observed values in the crop years of 1987–1988 and 1988–1989. Deviations were −18, −15, −28, and −26%, respectively, for the 28, 56, 84, and 112 kg N ha^{-1} treatments of 1987–1988. Among these predictions, the values for 56 and 112 kg N ha^{-1} treatments fell within ±1 standard deviation of the observed values. Deviations of predicted biomass from observed for the year 1988–1989 were −1, −20, −7, −14, and −7% for the 0, 28, 56, 84, and 112 kg N ha^{-1} treatments, respectively. All, except for the 28 kg N ha^{-1} treatment, biomass predictions were within ±1 standard deviation of the field-observed values. Biomass predictions during the crop year 1989–1990 showed more deviations from the observed, with only one prediction falling within ±1 standard deviation of the observed variability in the field. Prediction deviations from observed biomass for this year were 22, −19, −27, −24, and −37%, respectively, for the respective N treatments. Reasons for the poor biomass prediction this crop season were the same as those discussed for

Table 7. Genetic coefficients developed for winter wheat (cv. TAM 107). Values given in parentheses are the range used in calibration of the parameter.

No.	Parameter	Value
1	Relative amount that phenological development is slowed for each day of unfulfilled vernalization, assuming that 50 d of vernalization is sufficient for all cultivars	6.5 (0.5–8)
2	Relative amount that development is slowed when plants are grown in a photoperiod 1 h shorter than the optimum (which is considered to be 20 h)	3 (2–4)
3	Relative grain-filling duration based on thermal time (degree days above a base temperature of 1°C), where each unit increase above zero adds 20 degree days to an initial value of 430 degree days	8 (0–9)
4	Kernel number per unit weight of stem (less leaf blades and sheaths) plus spike at anthesis, 1/g	9.0 (2–10)
5	Kernel filling rate under optimum conditions, mg d^{-1}	4.2 (1–5)
6	Nonstressed dry weight of a single stem (excluding leaf blades and sheaths) and spike when elongation ceases, g	1.7 (1.5–2.0)
7	Phyllochron interval, °C	76 (60–90)

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grain yield above. A RMSE of 1442 kg ha^{-1} was observed in the biomass predictions of the model across different N treatments and crop seasons.

Water balance components (crop ET, runoff, and precipitation) and N uptake simulated by RZWQM are presented in Table 6. Maximum N uptake was predicted for the crop year of 1987–1988, with amounts ranging from 147 to 203 kg ha^{-1}. Maximum level of cumulative crop growing season ET (Table 6) also was predicted for the same year, with values ranging from 32.3 to 33.7 cm. Nitrogen uptake was predicted to be lower in 1988–1989 than in 1987–1988, with values ranging between 98 and 175 kg ha^{-1} for various levels of N applications. Lower total ET rates also were predicted for the same year, with values ranging from 18.9 to 19.2 cm for different N treatments. Nitrogen uptakes predicted for the year 1989–1990 were in the range of 81 to 160 kg N ha^{-1} for the various treatments. Leaching loss of N predicted by the model for all of the years and treatments were found to be negligible (less than 0.2 kg N ha^{-1}) as there was not enough rainwater available for movement of N beyond the root zone.

Though RZWQM does not predict crop phenological development explicitly, model simulations of growth stages show that 79 to 94% of the plant population entered reproductive (flowering) stage by the field-measured flowering dates during 1987–1988 crop season. During the 1988–1989 season, the percentage was 66 to 76%, and during the 1989–1990 season, the percentage was 89 to 92% of the plant population. Respectively, 90 to 99%, 60 to 75%, and 90 to 94% of the plant population was simulated to be in the ripening stage during the crop seasons of 1987–1988, 1988–1989, and 1989–1990 by the field-measured dates of physiological maturity.

Validation of CERES-Wheat

Mean RMSE for soil moisture predictions across different N treatments were 0.031, 0.074, and 0.071 cm^3 cm^{-3} for 1987–1988, 1988–1989, and 1989–1990 validation crop years, respectively (Table 5). Errors in soil water simulations were mainly due to errors in simulations of ET. During the three validation crop years, the model simulated cumulative ET with RMSEs 13.5, 9.2, and 10.6 cm, respectively (Table 6).

Grain yield simulations showed that CERES-Wheat responds to N application rates as measured in the field experiments (Fig. 3). Predicted yield response to different N application rates was in better agreement with the field measured in the crop seasons of 1987–1988 and 1989–1990. Rainfall recorded at the site during these crop seasons was 35 and 24 cm, respectively. However, in the low-rainfall (19 cm) crop season of 1988–1989, the model did not respond adequately to N applications above 28 kg N ha^{-1} treatment (Fig. 3). The model performed best in prediction of grain yield amounts in the crop season of 1987–1988 (best rainfall crop season compared with 1988–1989 and 1989–1990). Deviations of predicted values from observed were 1 (calibration), 23, 3, −3, and 13%, respectively, for 0 (calibration), 28, 56, 84, and 112 kg N ha^{-1} trials. The RMSEs of soil water predictions during this crop year were 0.023, 0.030, 0.028, 0.030, and 0.037 cm^3 cm^{-3}, respectively. Better soil moisture predictions led to better yield predictions by the model. Cumulative ET simulations by the model during this crop season were also found to be better than the other two crop seasons (Table 6). The crop year of 1988–1989 (driest year compared with 1988–1987 and 1989–1990) performed the poorest compared with the other two crop seasons. The absolute deviations of the observed from predicted values this year were 1, −20, −20, −24, and −25% for the respective N trials. Higher RMSEs, namely 0.064, 0.100, 0.052, 0.074, and 0.083 cm^3 cm^{-3}, respectively, for the five N treatments, of soil water predictions during this year (Table 5) contributed to poor prediction of grain yield. Errors in soil water predictions contributed to about 31% less N uptake by the crop during this crop season compared with the crop season of 1987–1988 (Table 6). Averaged across different N treatments, RMSE for ET prediction during this crop season was 9.2 cm. Predicted values of grain yields deviated from their observed values during the crop year of 1989–1990 by 14, −13, −27, −21, and −25% for the 0, 28, 56, 84, and 112 kg N ha^{-1} treatments, respectively. Poor prediction in soil water contents during this year also were observed, with RMSEs of 0.066, 0.056, 0.076, 0.076, and 0.088 cm^3 cm^{-3}, respectively, for the five N experiments. Errors in soil water simulations during this crop year led to 34% less N uptake compared with the 1987–1988 crop season. Seasonal average plant usable N content in the 0- to 180-cm soil profile under 0 kg N ha^{-1} treatment simulated for 1987–1988, 1988–1989, and 1989–1990 crop seasons was 27, 89, and 30 kg ha^{-1}, respectively. The RMSE of ET prediction was 10.6 cm. A RMSE value of 500 kg ha^{-1} was observed in the grain yield predictions across the five N regimes and three crop seasons.

CERES-Wheat biomass simulation results also showed that it responds well to N application rates as measured in the field experiments (Fig. 4). Model predictions of biomass amount also followed a similar trend as grain yield discussed above. The crop year of 1989–1990 performed the worst, with predictions deviating from field measured between –7 and –33% under different N treatments. Deviations of predicted biomass from observed values during the crop years of 1987–1988 and 1989–1990 were between –4 and –22% and –19 and 15%. A RMSE of 1247 kg ha^{-1} was observed in the biomass predictions of the model across different N treatments and crop seasons.

The CERES model predicted the highest amounts of N uptake in the 1987–1988 crop year, with values ranging between 62 and 159 kg N ha^{-1} across different N application rates (Table 6). N uptake rates varied between 76 and 88 kg ha^{-1} in 1988–1989 and between 49 and 84 kg ha^{-1} in 1989–1990. Model simulations of phenology show that the predicted dates of flowering and physiological maturity in all the years were reasonably good. Flowering dates were predicted within a range of –6 and +2 d, and physiological maturity dates were predicted within a range of –4 and +1 d.

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Model Applications for Nitrogen Management

Well calibrated and validated crop models in conjunction with long-term historical weather data can help in assessment of risks associated with weather variability for adopting various crop management strategies (Thornton and Wilkens, 1998). The simulation results can then be analyzed to come up with the best management strategy for a location in terms of economic yield return or other factors of interest to the user. First, the evaluated models were used to assess various N management effects on wheat yield under no-till rainfed conditions and possible weather conditions at Akron in eastern Colorado. The same initial soil water and N conditions and plant population density were used for each crop season, and the models were run every year independently from 1 January to harvest date with historical weather input from 1912 to 2001. Both of the models were run for a single planting date of 23 Sept. each year under no-till rainfed conditions. Nitrogen application rates simulated were 0, 28, 56, 84, and 112 kg N ha^{-1}, with either single dose at planting or split dose with 50% at planting followed by 25% each at 14-d intervals. Three N application methods were broadcast (on the soil surface), broadcast incorporated (soil depth: between 0 and 10 cm), and injected (soil depth: between 20 and 25 cm).

Second, the calibrated models were used to study crop rotation management. Two crop rotation systems (CW and W-F) were selected to compare their productivities and water and N use efficiencies. Here, WUE is defined as the grain yield per unit of water used in meeting the seasonal ET requirement of the crop or fallow, and N use efficiency (NUE) = (plant N uptake under a particular N treatment − plant N uptake of the 0 kg N ha^{-1} treatment)/amount of N applied. For crop rotation studies, model simulations were made continuously from 1 Jan. 1912 to 31 Dec. 2001, carrying over soil water and nutrient properties from one season to the other.

Cumulative probability function plots were made of simulated grain yield, total N uptake, residual soil N at harvest, and N leached beyond the root zone for the different N rates, application methods, dosages, and crop rotations. These cumulative probability function plots were further used to select the most viable N management option for eastern Colorado in terms of maximum grain yield and plant N uptake and minimum residual soil N at harvest and N leaching.

Nitrogen Application Rate

Figure 5 shows cumulative probability function plots of grain yield for different N rates based on historical weather data from 1912–2001. Yields predicted by RZWQM and CERES-Wheat in response to different N rates differed greatly (Fig. 5). Mean values of grain yield simulated respectively for the 0, 28, 56, 84, and 112 kg N ha^{-1} regimes were 1486, 2502, 2886, 2837, and 2816 kg ha^{-1} by RZWQM and 1183, 1596, 1710, 1755, and 1753 kg ha^{-1} by CERES-Wheat. The simulated mean grain yields of RZWQM were higher than those of CERES-Wheat under all five N rates by 303, 906, 1176, 1082, and 1013 kg ha^{-1}, respectively. One of the reasons for the differences in the yield predictions was the difference in the way the water balance modules of the models respond to variability in precipitation and other weather inputs across different years and interactions of water balance with the soil N processes. Also it can be seen from Fig. 3 that RZWQM simulated much higher grain yields in response to N application rates in 7 out of 12 validation experiments. In the crop season of 1988–1989, the driest of the validation crop seasons, RZWQM predicted substantially higher yields in all except one of the experiments. Due to the several differences in simulating physical and biological processes in the two models discussed earlier, simulation results are expected to be different. However, qualitatively speaking, the two models yield similar trends. Therefore, even though the grain yields predicted by the two models were different, both models predicted higher grain yield for the 28 and 56 kg N ha^{-1} treatments over the 0 kg N ha^{-1} treatment. It can also be noted from Fig. 5 that under the 28 kg N ha^{-1} regime, both models predicted higher probability of a given grain yield than under the 0 kg N ha^{-1} regime in all of the years of simulation. For the N application rate of 56 kg N ha^{-1}, RZWQM predicted higher grain yield than the 28 kg N ha^{-1} treatment in 100% of the simulation years while the CERES model predicted higher yields only in about 60% of

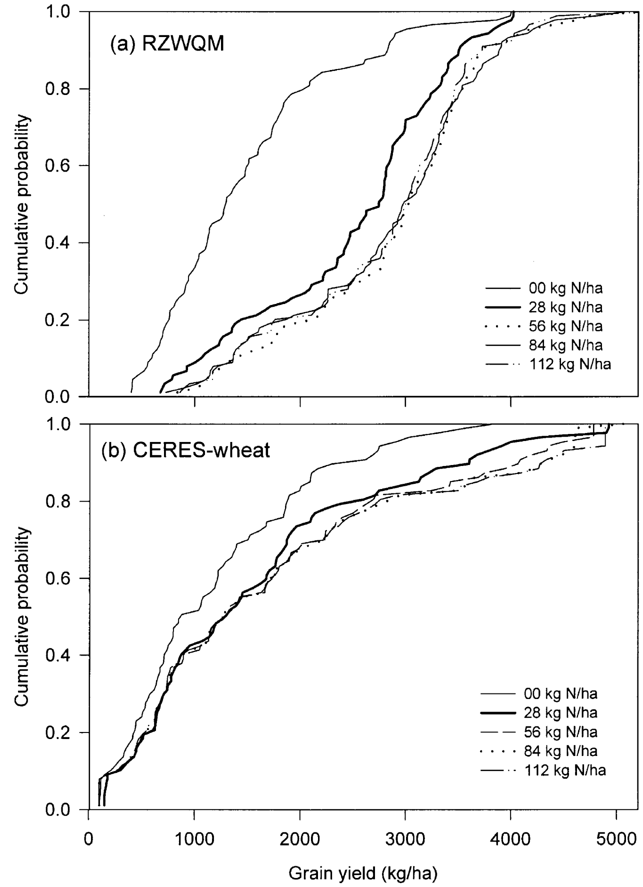

Fig. 5. Cumulative probability function plots of winter wheat grain yields simulated by RZWQM and CERES-Wheat models under different N treatments.

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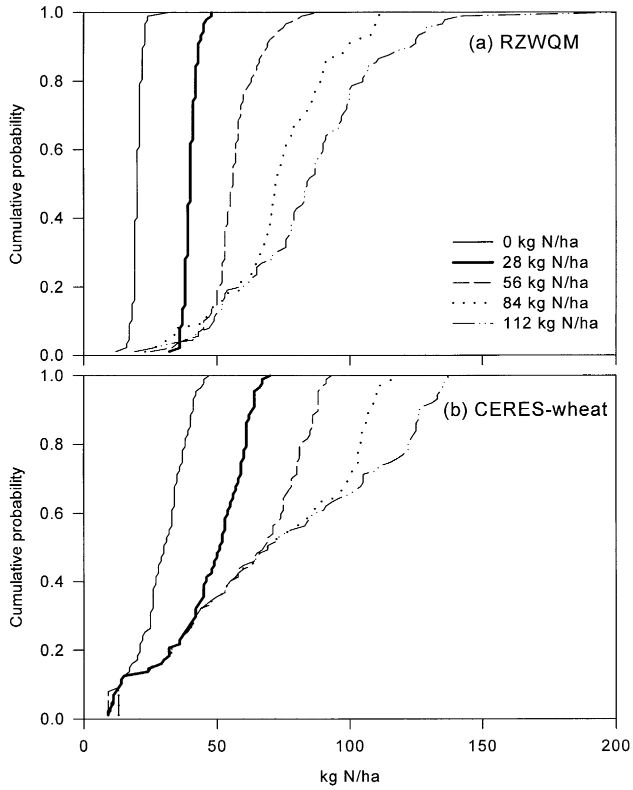

Fig. 6. Cumulative probability function plots of winter wheat whole plant N uptake simulated by RZWQM and CERES-wheat models under different N treatments.

the years. Both models predicted very little additional advantage in grain yield at N application rates greater than 56 kg N ha^{-1}. Thus, 56 kg N ha^{-1} treatment is the best N management option under rainfed conditions in the eastern Colorado. This application rate coincides with the N rate recommended for a grain yield goal of 3360 kg ha^{-1}, for soil test nitrate at 13 to 15 mg kg^{-1} in the 0- to 60-cm soil layer, and soil organic matter contents at 0 to 1% in the 0- to 30-cm soil layer (Davis and Vigil, 2000).

The model simulations show that N uptake predicted by the models differs substantially for all of the N regimes (Fig. 6). Nonetheless, both models show an increase in N uptake with application rate. Mean whole-plant N uptake simulated for the 0, 28, 56, 84, and 112 kg N ha^{-1} application rates were 20, 40, 57, 73, and 86 kg N ha^{-1} by the RZWQM and 29, 46, 59, 68, and 74 kg N ha^{-1} by the CERES-Wheat, respectively. Both models predict continued uptake of N by the crop with increased N application, but a corresponding increase in grain yield was reflected only up to 56 kg N ha^{-1} treatment.

Mean residual soil N was 30, 36, 37, 39, and 45 kg ha^{-1} when predicted by RZWQM and 21, 29, 44, 62, and 84 kg ha^{-1} when predicted by CERES-Wheat for the 0, 28, 56, 84, and 112 kg N ha^{-1} application rates, respectively (Fig. 7). Simulation results show that, averaged across the five N treatments, the CERES model predicted mineralization of about 33 kg N ha^{-1} and RZWQM about 49 kg N ha^{-1} in the Platner loam soil during a crop season. Mineralization in a W-F cropping

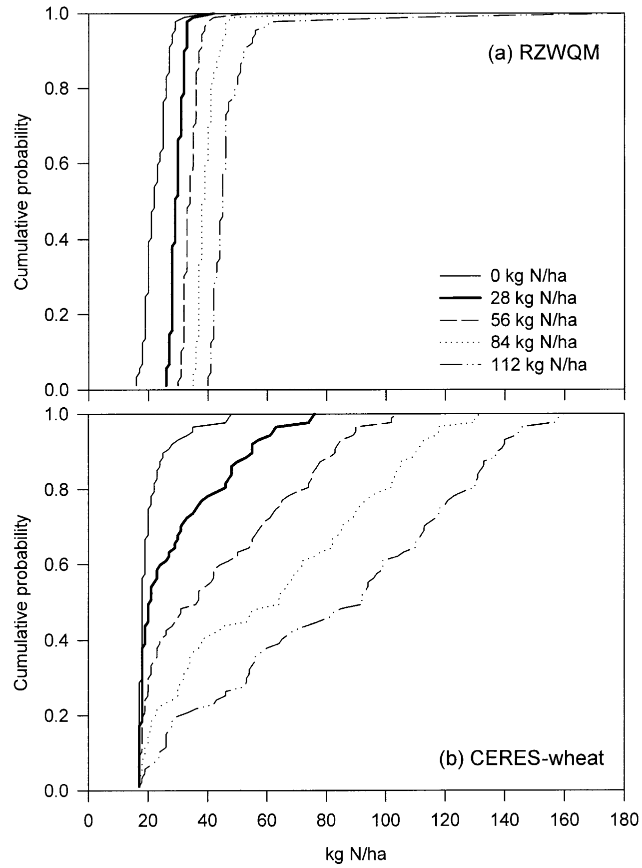

Fig. 7. Cumulative probability function plots of residual soil N at harvest of winter wheat simulated by RZWQM and CERES-Wheat models under different N treatments.

system in eastern Colorado was reported to be about 44 and 51 kg N ha^{-1}, respectively, in Weld silt loam and Keith clay loam soils (Kolberg et al., 1999). The model simulations are in reasonable agreement with these findings. Model simulations also show that the magnitudes of residual soil N simulated by the two models differed much from one another for all N treatment levels. Nonetheless, both models predicted an increase in soil residual N with N application rates.

There was very little predicted leaching loss of N owing to the low precipitation and little soil water movement beyond the root zone. The CERES-Wheat model simulated no N leaching loss. Mean leaching rates simulated by RZWQM for the five N application rates ranged from 3 to 4 kg N ha^{-1} across different treatments. Notwithstanding the amount, the model always predicted higher N leaching loss for 84 and 112 kg N ha^{-1} treatments compared with the 0, 28, and 56 kg N ha^{-1} treatments. Neither model predicted any loss of N in runoff water as expected.

Nitrogen Application Methods

As discussed above, further model simulations were made to study the response of wheat yield to three N application methods (i.e., broadcast, broadcast incorporated, and injected) and two dosages (i.e., single and split) at the 56 kg N ha^{-1} application rate. In RZWQM,

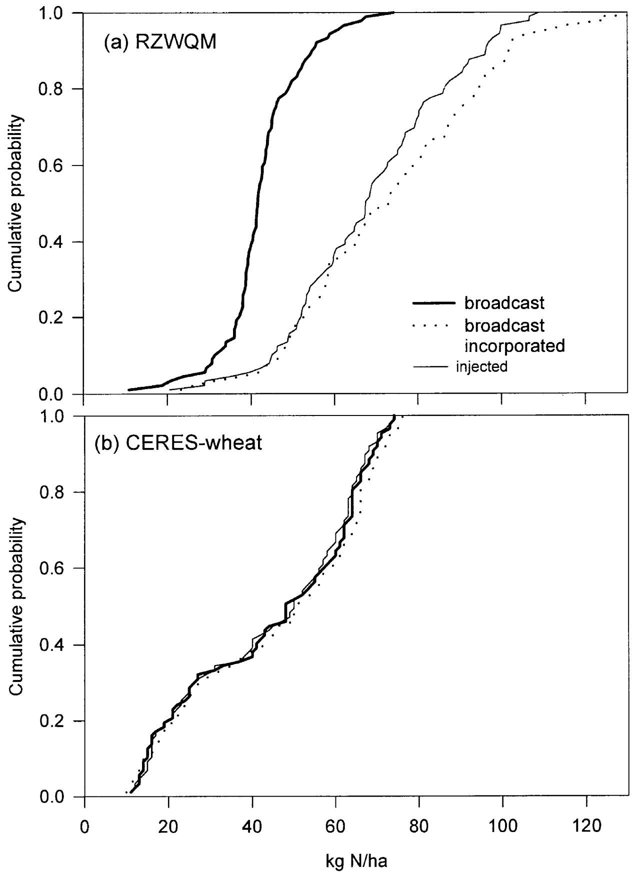

Fig. 8. Cumulative probability function plots of winter wheat N uptake simulated by RZWQM and CERES-Wheat for 56 kg N ha^{-1} treatment, applied using three methods, namely (i) broadcast, (ii) broadcast incorporated, and (iii) injected.

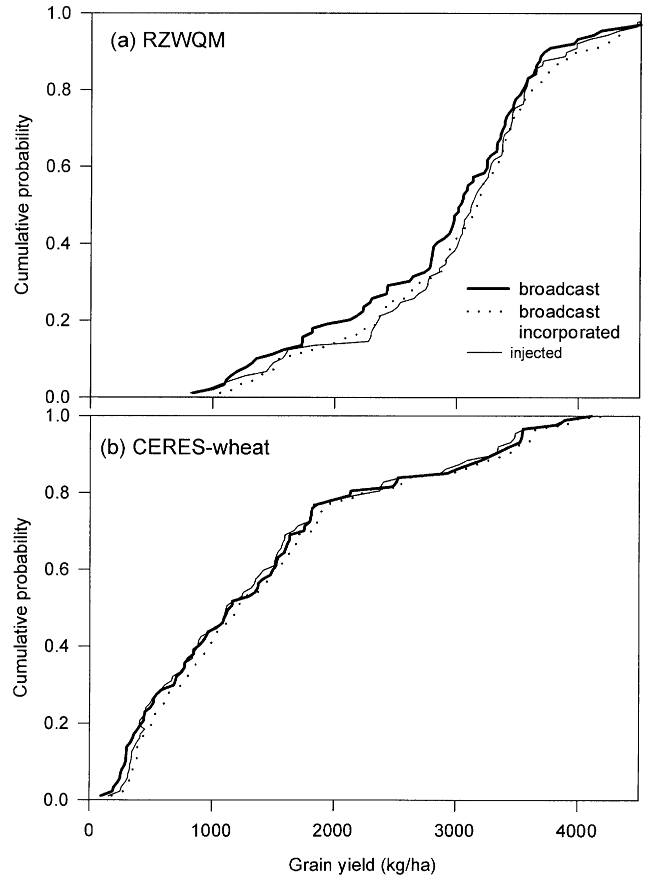

Fig. 9. Cumulative probability function plots of winter wheat grain yields simulated by RZWQM and CERES-Wheat for 56 kg N ha^{-1} applied using three methods, namely (i) broadcast, (ii) broadcast incorporated, and (iii) injected.

when N is broadcasted onto the soil surface, applied N is added into the 1-cm soil layer of the model. If incorporated broadcast, N is uniformly distributed in the incorporation zone (10 cm) by automatically scheduling a tillage event with field cultivation. In case of injection, applied N is distributed into the layer of destination (e.g., 25 ± 5 cm). In CERES-Wheat, simulations of different methods of N application are managed through inputs of depths of incorporation and degree of incorporation of applied fertilizer.

Simulations showed that both RZWQM and CERES-Wheat predict better N uptake when N was incorporated into the soil compared with the other two methods (Fig. 8). In RZWQM simulations, difference in N uptake between broadcast and other two N application methods were much greater than those simulated by the CERES model. One of the reasons for this is that N volatilization losses from soil are not simulated in CERES model under dryland conditions (Godwin and Singh, 1998). In RZWQM, NH_3 volatilization is modeled based on the partial pressure gradient of NH_3 in the soil and air (Shaffer et al., 2000). Ammonia volatilization predicted by RZWQM during the crop seasons of 1912 to 2001 averaged about 35% of the surface-applied ammonium nitrate, which is about twice as high as reported by He et al. (1999), who estimated a 17.6% potential maximum NH_3 volatilization from surface applied ammonium nitrate under experimental conditions, as predicted by Langmuir kinetic equation in an Alfisol (a Rivera fine sand). Better grain yield probabilities were simulated by both models for broadcast-incorporated method than the other two methods (Fig. 9). However, the differentiation between different methods as reflected in grain yields predicted using CERES-Wheat predictions was much less than RZWQM.

Since broadcast-incorporated method is superior to the other two methods, we further investigated the single dose application and split application on N uptake and grain yield. Shown in Fig. 10a and 10b are the cumulative probability function plots of N uptake rates simulated by the two models in response to a single application at planting and a split application with 50% at planting followed by 25% each at 14-d intervals. It can be seen from Fig. 10 that in most of the simulation years, both models simulated better N uptake in response to split application than single application. Corresponding cumulative probability function plots for grain yields are shown in Fig. 11a and 11b where in most of the simulation years, the models predicted better probability of grain yield return under split application than single application.

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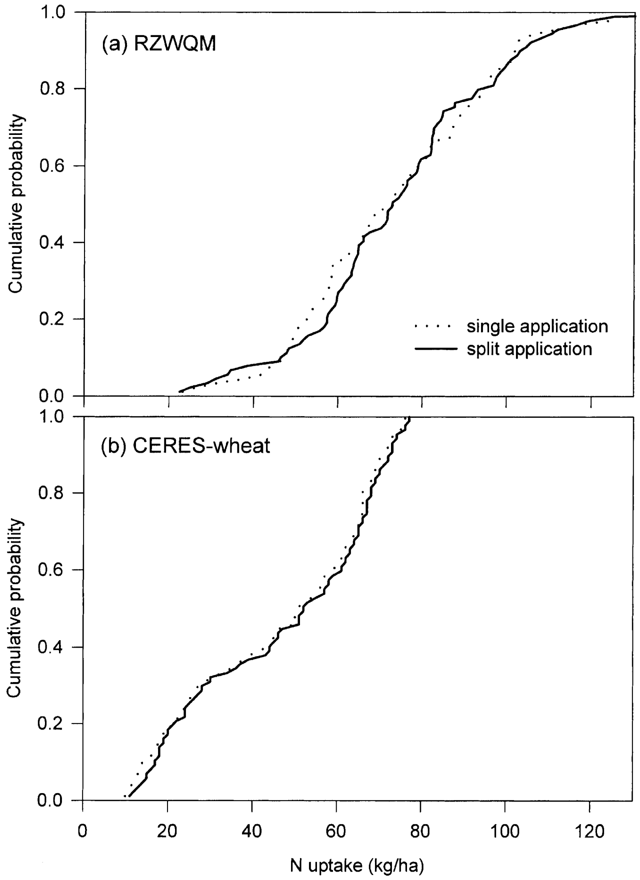

Fig. 10. Cumulative probability function plots of winter wheat N uptakes simulated by RZWQM and CERES-Wheat for 56 kg N ha^{-1} applied as broadcast incorporated in a single application and split application of 50% at planting followed by 25% each at 14-d intervals.

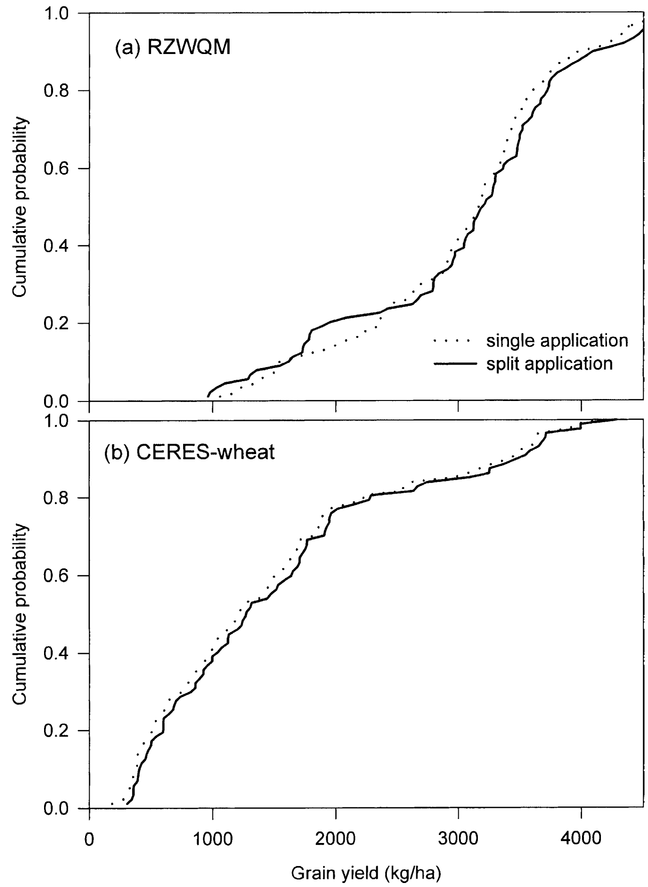

Fig. 11. Cumulative probability function plots of winter wheat grain yields simulated by RZWQM and CERES-Wheat for 56 kg N ha^{-1} applied as broadcast incorporated in a single application and split applications of 50% at planting followed by 25% each at 14-d intervals.

Crop Rotation

As discussed above, it is clear from the model simulations that N applied at a rate of 56 kg N ha^{-1} broadcast-incorporated in split applications is the best N management practice for winter wheat under rainfed conditions in eastern Colorado. Though winter wheat production systems with a fallow year are on the decline in the USA, the W-F rotation continues to dominate rainfed agriculture in the semiarid areas receiving less than 350 mm of annual precipitation (Dhuyvetter et al., 1996; Janosky et al., 2002). Optimization of WUE of dryland agricultural system is a prime concern in rainfed cropping systems in semiarid conditions, in addition to the production stability and sustainability issues (Hatfield et al., 2001). In light of these concerns, long-term simulations (1912–2001) with RZWQM and CERES-Wheat under both a W-F production system and a CW production system were conducted. Grain yield production and WUE and NUE of these systems as discussed above were compared to study the viability of these rotations in eastern Colorado.

Given in Fig. 12a and 12b are the cumulative probability function plots of winter wheat grain yields simulated by RZWQM and CERES in response to the no-till CW and W-F rotations under the 56 kg N ha^{-1} regime applied as broadcast incorporated in split applications of 50% at planting followed by 25% each at 14-d intervals. Both models simulated higher grain yields under W-F rotation system than under CW. RZWQM and CERES simulated 5 and 41% higher grain yields, respectively, under the W-F rotation than under CW. However, the increase in grain yield in 50% of the crop years (i.e., the nonfallow years) is not adequate to compensate for the loss in grain yield during the 50% fallow years.

Both models predicted lower WUE under W-F than under CW rotation (Fig. 13a). Declines in predicted WUE were 49 and 11% by RZWQM and CERES, respectively. Hence, to increase WUE, more intensive CW cropping system is preferred over less crop intensive W-F rotation. Farahani et al. (1998) reported that, though fallowing land to increase soil water storage has been considered a viable and necessary practice in rainfed semiarid agriculture, precipitation use efficiency may increase with reduced tillage systems with more intensive cropping rotations. The WUE gains can be due to using water for crop growth that otherwise is lost during fallow by soil evaporation, runoff, or deep percolation process. Our model simulation results support these findings. RZWQM simulated a NUE of 66%

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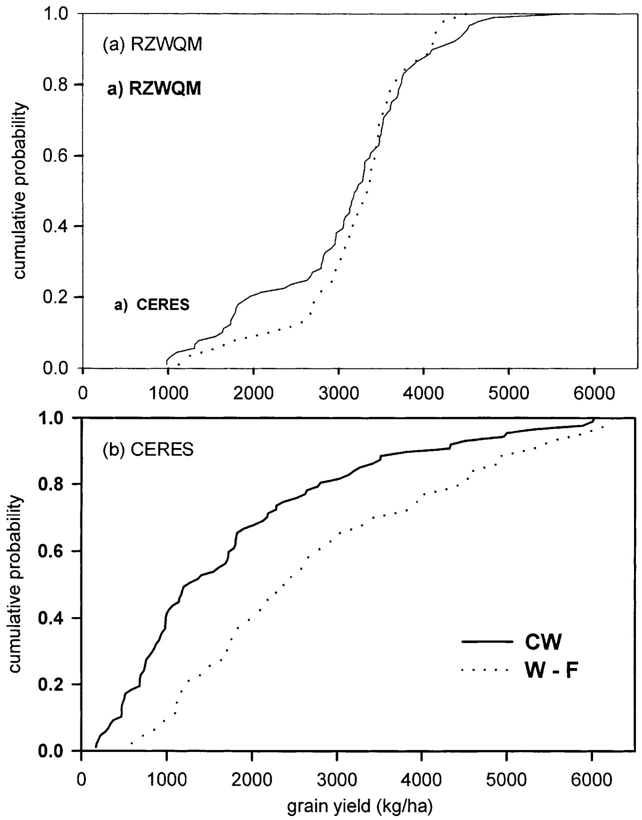

Fig. 12. Cumulative probability function plots of winter wheat grain yields under continuous wheat (CW) and wheat–fallow (W-F) rotations simulated by RZWQM and CERES-Wheat for 56 kg N ha^{-1} applied as broadcast incorporated in split applications of 50% at planting followed by 25% each at 14-d intervals.

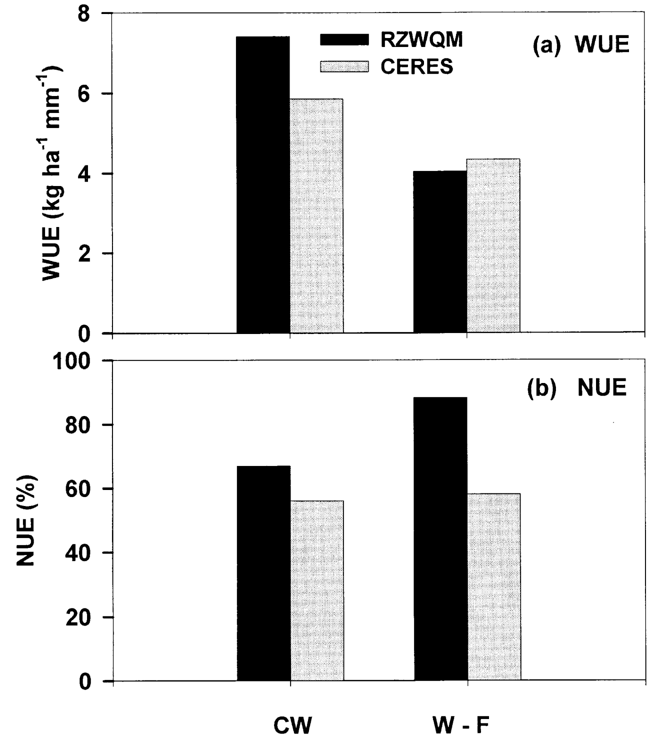

Fig. 13. (a) Water use efficiency (WUE) response on grain yield, and (b) N use efficiency (NUE) of continuous wheat (CW) and wheat–fallow (W-F) crop rotations. Water use efficiency is defined as the grain yield per unit of water used in meeting the seasonal evapotranspiration requirement of the crop or fallow, and NUE = (plant N uptake under a particular N treatment − plant N uptake of the 0 kg N/ha treatment)/amount of N applied.

for CW and 88% for W-F systems (Fig. 13b). Simulations of CERES-Wheat showed only marginal difference in NUEs between the two systems with 56 and 58% for CW and W-F systems, respectively.

CONCLUSIONS

In this study, we assessed the capabilities of RZWQM and CERES-Wheat models for simulating winter wheat growth and yield at different N applications under rainfed conditions in the semiarid climate of eastern Colorado. Results of the study showed that RZWQM performed better than CERES-Wheat in soil moisture predictions while the crop yield predictions were comparable. The generic crop growth model of RZWQM does not simulate separate leaf numbers or tillers. The model can be further improved for simulation of leaves and tillers for better predictions of crop development and growth for tactical applications of the model for winter wheat management. In rainfed winter wheat cultivation in the semiarid climate of eastern Colorado, responses of the two models to N application rates during relatively good rainfall seasons were comparable, but during low-rainfall crop seasons, RZWQM responded better to N application rates. CERES-Wheat predictions of dates of flowering and physiological maturity were reasonably good for use in crop management applications and research. Generic crop model of RZWQM does not predict crop phenology explicitly for applications in crop management. The model needs modifications for explicit predictions of crop phenology.

Long-term simulations of winter wheat in eastern Colorado using the validated RZWQM and CERES-Wheat models and weather data from 1912 through 2001 revealed that split applications of 56 kg N ha^{-1} with 50% broadcast-incorporated at planting followed by 25% each broadcast at 14-d intervals are the best N management options under rainfed conditions when grain yield, crop N uptake, residual soil N, and N leaching are all taken into consideration. Model simulations also showed that the W-F cropping system is less preferable than the CW system in terms of WUE.

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