Simulating Alternative Dryland Rotational Cropping Systems in the Central Great Plains with RZWQM2

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Modeling

ABSTRACT

Long-term crop rotation effects on crop water use and yield have been investigated in the Central Great Plains since the 1990s. System models are needed to synthesize these long-term results for making management decisions and for transferring localized data to other conditions. The objectives of this study were to calibrate a cropping systems model (RZWQM2 with the DSSAT v4.0 crop modules) for dryland wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), and proso millet (*Panicum miliaceum* L.) production in the wheat–corn–millet (WCM) rotation from 1995 to 2008, and then to evaluate the model from 1992–2008 for two additional rotations, wheat–fallow (WF) and wheat–corn–fallow (WCF) on a Weld silt loam soil under no-till conditions. Measured biomass and grain yield for the above three rotations were simulated reasonably well with root mean squared errors (RMSEs) ranging between 1147 and 2547 kg ha^{-1} for biomass, and between 280 and 618 kg ha^{-1} for grain yield. Corresponding index of agreement (d) ranged between 0.70 and 0.95 for biomass, and between 0.87 and 0.97 for grain yield. The validated model was further used to evaluate two additional crop rotations: wheat–millet–fallow (WMF) and wheat–corn–millet–fallow (WCMF) (1993–2008) without prior knowledge of the two rotations. We found that the model simulated the mean and range of yield and biomass of the three crops well. These results demonstrated that RZWQM2 can be used to synthesize long-term crop rotation data and to predict crop rotation effects on crop production under the semiarid conditions of eastern Colorado.

TRADITIONAL WINTER WHEAT production in a wheat–fallow rotation with conventional mechanical tillage in the Great Plains faces a number of natural resource conservation and quality issues that can affect the productivity and livelihood of the region's farmers. Because water is generally the most yield-limiting factor in the semiarid climate of the Great Plains, a 14-mo fallow period between crops has traditionally been used to increase stored soil water before planting, thereby increasing the subsequent crop yield (Greb, 1979). Notwithstanding the potential yield-stabilizing merits of fallow, this practice has often been the cause of severe soil erosion and quality degradation in the region (Bowman et al., 1999). The loss of soil quality resulting from conventionally tilled fallow has raised concerns about the long-term sustainability of wheat– fallow.

Sustainable farming systems must make use of diversified crops and rotations to mitigate the negative impacts of the wheat–fallow monoculture in the Great Plains (Anderson et al., 1999; Bowman et al., 1999; Shanahan et al., 1988; Norwood et al., 1990: Dhuyvetter et al., 1996). Long-term experiments that focus on reducing the amount of summer fallow time and reversing the soil degradation using no-till were established in eastern Colorado in 1985 (Peterson and Westfall, 2004). In those experiments, cropping system intensification (reduced fallow frequency) increased annualized grain and residue yields by 75 to 100%, and net return to farmers by 25 to 45%. In addition, soil organic carbon was found to be impacted significantly to a depth of 5 cm with an increase of 35% in the 12 yr of study compared to the WF system (Sherrod et al., 2003). Another cropping system experiment with decreased tillage and various degrees of increased cropping intensity involving a variety of summer crops (such as corn, proso millet, foxtail millet (*Setaria italica* L. Beauv.), sorghum [*Sorghum bicolor* (L.) Moench], field pea (*Pisum sativum* L.), sunflower (*Helianthus annuus* L.), canola (*Brassica napus* L.), triticale (*X Triticosecale rimpaui* Wittm, etc.) was established in 1991 at the Central Great Plains Research Station, USDA-ARS, Akron, CO in the Great Plains of the United States (Anderson et al., 1999).

Many potential alternative crop rotations for the semiarid Great Plains have been investigated since the 1990s with promising results that encourage farmers to adopt environmentally friendly farming practices (Acosta-Martinez et al., 2007; Vigil and Nielsen, 1998; Nielsen et al., 1996). However, uncertainty exists with regard to the specific impacts of these alternative cropping systems on sustainable crop production, natural resource conservation, and long-term soil and water quality issues. Also, in view of the large-scale spatial heterogeneity associated with the landscapes in the semiarid regions, questions arise on the validity of extrapolating the location-specific

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Published in Agron. J. 102:1521–1534 (2010)
Published online 17 Aug. 2010
doi:10.2134/agronj2010.0141

Abbreviations: C, corn; CT, conventional tillage; ET, evapotranspiration; F, fallow; GDD, growing degree days; LAI, leaf area index; M, proso millet; NT, no tillage; PUE, precipitation use efficiency; RMSE, root mean squared error; RZWQM, Root Zone Water Quality Model; W, winter wheat; WCF, wheat–corn–fallow; WCM, wheat–corn–millet; WCMF, wheat–corn–millet–fallow; WF, wheat–fallow; WMF, wheat–millet–fallow; WUE, water use efficiency.

Table 1. Monthly total precipitation received at the experimental site during 1992 to 2008.

Month	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	1908–2008
	mm																	
January	14	6	10	22	8	13	1	2	6	22	2	6	8	3	1	12	4	9
February	5	14	5	9	1	13	32	4	8	11	2	10	22	3	2	4	16	9
March	50	13	2	22	29	2	4	8	40	25	2	59	5	11	16	18	13	20
April	6	47	53	62	12	22	18	52	41	34	13	67	39	42	23	64	29	42
May	17	27	29	145	116	55	25	80	20	107	14	101	43	62	37	61	41	74
June	120	45	6	121	65	80	10	62	19	34	43	108	64	86	18	35	66	62
July	52	114	70	39	83	31	102	40	66	67	3	23	43	75	58	47	44	66
August	102	24	30	20	68	62	56	173	55	58	87	46	72	94	87	95	162	56
September	1	23	8	57	86	25	8	39	39	44	38	4	43	10	29	15	34	30
October	21	95	73	10	12	59	17	12	49	17	28	0	19	75	16	4	34	23
November	19	26	26	15	1	7	27	12	8	5	8	3	23	19	2	3	20	13
December	6	12	13	2	1	11	5	15	6	0	1	5	6	6	26	61	9	11
Annual	413	446	325	524	482	380	305	499	357	424	241	432	387	486	315	419	472	415
Mar-June	193	132	90	350	222	159	57	202	120	200	72	335	151	201	94	178	149	198
May-Sept.	292	233	143	382	418	253	201	394	199	310	185	282	265	327	229	253	347	288
June-Aug.	274	183	106	180	216	173	168	275	140	159	133	177	179	255	163	177	272	184

findings from one location to other climates and soils of the region using conventional statistical techniques.

In this context, agricultural systems simulation models based on the current scientific knowledge of the system have the potential to provide decision support in designing efficient alternative cropping systems (Ahuja et al., 2006; Jones et al., 2003; Saseendran et al., 2005a). The Root Zone Water Quality Model (RZWQM2) is a comprehensive agricultural system model with the capacity to integrate and synthesize the biological, physical, and chemical processes for simulation of the impact of tillage, water, agricultural chemical, and crop management practices on crop production and water quality (Ahuja et al., 2000). Development of RZWQM2 combined the detailed simulations of soil surface residue dynamics, tillage, and other soil management practices, and detailed soil water and soil C/N processes of RZWQM with the detailed crop-specific plant growth models available within the Decision Support System for Agrotechnology Transfer (DSSAT) v. 4.0 (Saseendran et al., 2009; Ma et al., 2009; Jones et al., 2003). Saseendran et al. (2009) adapted the CERES crop modules available in RZWQM2 to simulate spring triticale, proso millet, and foxtail millet. An earlier version of the RZWQM-DSSAT hybrid was successfully used for simulation and development of management practices for corn and soybean [*Glycine max* (L.) Merr.] in Iowa (Saseendran et al., 2007), soybean in Colorado (Ma et al., 2005), and wheat and corn in the North China Plain (Fang et al., 2008).

A number of previous studies have used RZWQM and DSSAT v4.0 to model research results from the USDA-ARS Central Great Plains Research Station at Akron, CO as typical of the semiarid central Great Plains environment. Saseendran et al. (2004) adapted the generic crop module in RZWQM for simulation of winter wheat and developed N management strategies for wheat under rainfed conditions in eastern Colorado. Using both RZWQM and CERES-Maize (separately), Saseendran et al. (2005b) modeled planting date effects on corn yield and developed optimum planting windows for the crop. Saseendran et al. (2008) used the CERES-maize model within DSSAT v4.0 to develop limited irrigation water management alternatives for corn in the semiarid climate of Akron, CO. Saseendran et al. (2009) used RZWQM2 with the adapted CERES modules to model responses of dryland spring triticale, proso millet, and foxtail millet to initial soil water in the Great Plains.

Saseendran et al. (2005a) used data from 1992 to 2002 from the Akron Alternative Crop Rotation experiment to simulate three wheat-based cropping systems using the generic crop model available in RZWQM parameterized to simulate winter wheat and corn. However, that study was predominantly focused on tillage effects in the WF rotation and comparing WF with WCF. There is a need to use the CERES crop modules in RZWQM2 to simulate more crop rotations and for a longer period of time. Most importantly, it is essential to demonstrate whether a calibrated model can be used to "construct" a crop rotation that is reasonable before a field experiment even starts.

Therefore, our objectives were to (i) calibrate the DSSAT crop modules in RZWQM2 for simulation of dryland WCM rotation from 1995 to 2008; (ii) evaluate the calibrated model for the WF and WCF rotations for a longer period of time (1992–2008); and (iii) "construct" or "propose" two new crop rotations (WMF and WCMF) using the calibrated model without previous knowledge of the two rotations revealed to the model user (1993–2008). The results of this study should build confidence on extending the use of models in cropping sequence selection for other soil and climate conditions.

MATERIALS AND METHODS

Field Experiments

Data were obtained from the long-term dryland Alternative Crop Rotation experiment conducted at the USDA-ARS Central Great Plains Research Station (40°09′ N, 103°09′ W, 1384 m) located 6.4 km east of Akron, CO. Mean annual precipitation is 415 mm of which 288 mm is received from May to September (Table 1). This experiment was established in 1991 primarily for assessing effects of various tillage intensities and crop sequences on crop productivity, soil quality, precipitation storage efficiency, water use efficiency, and economic and environmental sustainability to make recommendations regarding systems that might replace the traditional WF system and reduce the frequency of fallow (Bowman and Halvorson, 1997; Anderson et al., 1999). In this experiment 20 crop rotations involving combinations of six crops and fallow, and three tillage treatments were established. Four cropping intensities were used as fallow frequency declined (one crop in 2 yr, two crops in 3 yr, three crops in 4 yr, and continuous cropping) as described by Bowman et al. (1999). Plots were 9.1 by 30.5 m with east–west row direction. Every phase of every rotation appeared every year, replicated three times in a randomized complete block design on a Weld silt loam (fine, smectitic, mesic Aridic Argiustolls). Detailed descriptions of cultural practices, plot area, and experimental design were reported by Bowman and Halvorson (1997) and Anderson et al. (1999). For this study, we used data from the WF (1992–2008), WCF (1992–2008), and WCM (1995–2008) rotations to calibrate and evaluate the model. All rotations were managed under NT conditions in which herbicides (primarily glyphosate) were used to control weeds during fallow periods. The data used in the current modeling study comprised eight data sets of 14 to 17 yr each: (i) WF-W (wheat phase in 1992), (ii) WF-F (fallow phase in 1992), (iii) WCF-W (wheat phase in 1992), (iv) WCF-C (corn phase in 1992), (v) WCF-F (fallow phase in 1992), (vi) WCM-W (wheat phase in 1995), (vii) WCM-C (corn phase in 1995), and (viii) WCM-M (millet phase in 1995). Two additional crop rotations (WMF and WCMF) were reserved to compare with "proposed" WMF and WCMF rotations (constructed from the management data of the other rotations, WF, WCF, and WCM) using the calibrated model and were withheld from the model users.

Winter wheat cultivars planted were 'TAM 107' from 1991 to 1995, 'Akron' from 1996 to 2005, and 'Danby' from 2006 to 2008. Corn hybrids 'Pioneer Hybrid 3732' from 1992 to 1997, 'DK493 BT' in 1998 and 1999, 'DKC49–92' in 2000, 'NK4242 BT' from 2001 to 2003, and 'N42B7' from 2004 to 2008 were used. Relative maturity of hybrids was 101 d from 1992 to 1997 and 99 d for subsequent years. Proso millet cultivars planted were 'Sunup' from 1995 to 2000, and from 2002 to 2005, and 'Huntsman' in 2001 and from 2006 to 2008.

Fertilizer N was applied to achieve projected yields of 2688 kg ha^{-1} for winter wheat, 4100 kg ha^{-1} for corn, and 2000 kg ha^{-1} for proso millet. Actual fertilizer applied for different crops in different crop sequences over different rotation phases and seasons ranged between 12 and 67 kg N ha^{-1} for winter wheat, 34 and 95 kg N ha^{-1} for corn, and 0 and 84 kg N ha^{-1} for millet. All crops were grown under rainfed conditions. Wheat planting occurred between 18 and 26 September, corn planting occurred between 29 April and 18 May, and proso millet planting occurred between 6 and 25 June in individual crop seasons. Average seeding densities were 70 kg ha^{-1} for wheat, 16,000 seeds ha^{-1} for corn, and 15 kg ha^{-1} for proso millet.

Soil water measurements were made with a neutron probe (Model 503, Hydroprobe, CPN International, Martinez, CA) at two locations near the center of each plot at depths of 45, 75, 105, 135, and 165 cm. Time-domain reflectometry (Trase System I, Soil Moisture Equipment Corp., Santa Barbara, CA) was used to measure soil water in the 0- to 30-cm depth. Measured soil water from the surface to 180 cm depth was used for calculating crop evapotranspiration (ET) employing the water balance method, assuming deep percolation and runoff losses in the experimental plots were negligible. Daily precipitation recorded in the plot area, and maximum and minimum air temperature, solar radiation, wind speed, and relative humidity recorded by an automated weather station approximately 350 m from the plot area provided input for model simulations.

Leaf area index (LAI) and biomass measurements were made periodically throughout the growing season. The LAI was estimated using a plant canopy analyzer (LAI-2000, LI-COR, Lincoln, NE) with the 270° view restrictor to mask the operator (i.e., 270° open, 90° masked). Two sets of one measurement above and four measurements below canopy were taken on a diagonal transect between crop rows in the center of the plot. Dry matter sample size was 2 m of a single row. Samples were oven-dried at 60°C until weight remained constant.

Model Inputs

The RZWQM2 model requires detailed data for crop management, soil, and weather. Crop management data needed are planting date and depth, row spacing, and plant population. Also, amount, dates, and methods of fertilizer applications, are required. These data were collected for the current experiment. In addition, the model also requires initial inputs of dry and wet soil albedo (shortwave reflectivity), crop canopy albedo, and crop residue albedo for potential ET computations. Based on Ahuja et al. (2000) these parameters were assumed to be 0.25, 0.20, 0.35, and 0.30, respectively for all three crops. Soil physical and hydraulic properties for silt loam soil as available in the RZWQM2 model database (Ahuja et al., 2000) were used for simulations. The weather variables required by RZWQM2 are daily solar radiation, maximum and minimum air temperatures, wind speed, relative humidity, and precipitation. We assumed the daily precipitation events to be storms of 120 min duration to create the break point precipitation records required by RZWQM2.

Precipitation recorded during the experimental period (1992–2008) exhibited high inter-annual variability in amount and seasonal distribution (Table 1). From 1992 to 2008, annual precipitation ranged from 241 mm (2002) to 524 mm (1995). From March to June (roughly the spring growth period for winter wheat) precipitation ranged from 57 mm (1998) to 350 mm (1995). From May to September (roughly the corn growth period) precipitation varied between 143 mm (1994) and 418 mm (1996). From June to August (roughly the proso millet growth period) precipitation varied between 106 mm (1994) and 275 mm (1999).

Model Calibration

In this study, simulation of wheat, corn, and proso millet was conducted using the CSM-CERES model in RZWQM2. Initial parameters were obtained from Saseendran et al. (2005a) for wheat and corn and from Saseendran et al. (2009) for proso millet. The most commonly accepted method for calibrating cultivar parameters of the CSM-DSSAT crop models in RZWQM2 is a step-by-step procedure following the systematic procedure recommended by Boote (1999) by calibrating soil moisture first, followed by plant growth (phenology, biomass, and yield in that order). The detailed model calibration procedure can be found in Saseendran et al. (2005a, 2009).

Table 2. Modified species parameters for simulation of winter wheat cultivars (TAM 107, Akron, and Danby) at Akron, CO.

No.	Parameter name	Value	
		Calibrated	Original value
1	Emergence phase duration (PECM), thermal units per cm depth.	15	10
2	Germination phase duration (PEG), hydrothermal units.	15	10
3	Lethal temperature for 50% kill of unhardened seedling (LT50S), °C.	−5	−6
4	Nitrogen stress factor, senescence, upper (NFSU), fraction.	0.8	0.3
5	Temperature response, photosynthesis (TRPHS), °C.	0, 10, 25, 35	−5, 10, 15, 35

The WCM rotation (WCM-M with millet as the first crop in 1995) was selected for calibration because it contained all three crops. The other two WCM phases along with WF and WCF rotations were used for model validation. Calibration of the various parameters of soil hydraulic properties, nutrient properties, and plant growth parameters for the experimental site and crops is critical for accurate simulations of any agricultural system (Ahuja and Ma, 2002). In this study, we used the soil hydraulic and nutrient properties for a silt loam soil developed by Saseendran et al. (2009) at the same location. Plant parameters from previous studies were used as initial values for calibration (Saseendran et al., 2008, 2009). The parameter values for the corn cultivar 'Pioneer 3732' from Saseendran et al. (2008) were used as initial values for 'DKC49–92', 'NK4242 BT', and 'N42B7' in this study. The parameter values for the proso millet cultivar 'Sunrise' from Saseendran et al. (2009) were used for 'Sunup' and 'Huntsman' for simulations using the DSSAT 4.0 models in RZWQM2. As there were no studies available in the literature for the wheat cultivars 'TAM 107' and 'Danby', we developed new parameters for wheat from cultivars available in DSSAT4.0 following the systematic procedure recommended by Boote (1999) for calibration.

Simulation results were assessed using root mean squared error (RMSE), Eq. [1], between simulated and observed values and the index of agreement (d), Eq. [2], between measured and simulated parameters (Willmott, 1981).

$$\mathrm{RMSE}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i-O_i)^2} \qquad [1]$$

$$\mathrm{d}=1.0-\frac{\sum_{i=1}^{n}(P_i-O_i)^2}{\sum_{i=1}^{n}(|P_i-O_{avg}|+|O_i-O_{avg}|)^2} \qquad [2]$$

where P_i is the ith simulated value, P_{avg} is the average of the simulated values, O_i is the ith observed value, O_{avg} is the average of the observed values, and n is the number of data pairs. The index of agreement varies between 0 (poor prediction) and 1 (perfect prediction).

RESULTS AND DISCUSSION

Model Calibration

We followed the systematic procedure recommended by Boote (1999) for calibration of all the model parameters related to the species, ecotype, and cultivars (genetic) of winter wheat, corn, and proso millet crops used in the simulations. For simulation of the three winter wheat cultivars ('TAM 107', 'Akron', and 'Danby') in the WCM rotation, we modified five species-specific parameters in the CERES-wheat module to better match the simulated growth and development of the crop with the measured data (Table 2). In the eco-type parameter file we used −30°C for the cold tolerance when fully hardened, as there were years when daily minimum temperatures of similar magnitude did not appear to affect crop performance at the site. We did not change any of the species-specific parameters or ecotype parameters for corn and proso millet.

In addition to species-specific and ecotype parameters, a given set of parameters specific to each cultivar used in the study needed to be defined (Tables 3 and 4). In the current simulations, our first attempt was to make use of the cultivar parameters for the corn and proso millet crops developed in earlier studies at Akron (Saseendran et al., 2009). However, use of different hybrids of corn and varieties of proso millet during the study period necessitated some calibration of these parameters for each cultivar. The corn cultivar parameters developed by Saseendran et al. (2008) for Pioneer 3732 were adjusted slightly for simulations of the five hybrids used in the current study (Table 3).

Simulation of winter wheat using the CERES-wheat module in RZWQM2 at Akron had not previously been done. Hence, we calibrated the cultivar parameters for the first time following the procedure outlined by Boote (1999) for calibration of the model parameters. One set of parameters (Table 3) was found to work well for simulation of all three cultivars ('TAM 107', 'Akron', and 'Danby').

For simulation of proso millet cultivars Sunup and Huntsman using the CERES-proso millet module in RZWQM2, we modified the cultivar parameters developed previously by Saseendran et al. (2009) for Sunrise. One set of parameters was found to be reasonable for simulating both cultivars (Table 4). Calibration of the above cultivar parameters was performed using the grain yield, biomass, LAI, and soil water content data collected in the WCM-M (i.e., WCM beginning with the millet phase in 1995) from 1995 to 2008. Due to the large number of cropping sequences and plots (198) in the Akron Alternative Crop Rotation experiment, only grain yield and biomass at crop harvest were collected regularly and available for calibration simulations. Leaf area index measurements were mostly available in 6 yr (2002, 2003, 2005, 2006, 2007, 2008), and soil water data were available at planting and harvest in all 14 yr (1995–2008).

From 1995 to 2008, five winter wheat, four corn, and five millet crops were grown in the WCM-M rotation. The corn data collected in the year 1997 was excluded from the analysis as the measured grain yield showed a standard deviation of 2108 kg ha^{-1} about the mean (1472 kg ha^{-1}), probably a result of a mid-season hail storm. All crops were simulated sequentially with the simulation starting on 1 Jan. 1995 and ending

Table 3. Cultivar parameters (genetic coefficients) for corn hybrids† and winter wheat cultivars‡ developed for simulations using the CERES-maize and CERES-wheat modules in RZWQM2.

Parameters	Definitions	Corn		Wheat
		Values used by Sassendran et al. (2008)	Current calibrated values	Current calibrated values
P1	Thermal time from seedling emergence to the end of Juvenile phase during which the plants are not responsive to changes in photoperiod (degree days) (corn)	290	300	–
P1V	Relative amount that development is slowed for each day of unfulfilled vernalization, assuming that 50 d of vernalization is sufficient for all cultivars (wheat).	–	–	55
P1D	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) (wheat).	–	–	90
P2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development is at maximum rate, which is considered to be 12.5 h (corn).	0.8	0.8	–
P5	Thermal time from silking (or begin grain filling) to physiological maturity (corn, wheat).	615	600	350
G1	Kernel number per unit weight of stem (less leaf blades and sheaths) plus spike at anthesis (no. g^{-1}) (wheat).	–	–	35
G2	Maximum possible number of kernels per plant (corn) or Kernel filling rate under optimum conditions (mg d^{-1}) (wheat).	690	600	11
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg d^{-1}) (corn) or Nonstressed dry weight of a single stem (excluding leaf blades and sheaths) and spike when elongation ceases (g) (wheat).	9.6	9.6§	1.8
PHINT	Phyllochron interval (degree days) (corn, wheat).	38.9	43.9	60.0

† Pioneer 3732, Dekalb 493 BT, DKC-49–92, N4242BT, and N42B7.

‡ TAM 107, Akron, and Danby

§ G3 = 9.6 for Pioneer 3732 and Dekalb 493 BT; G3 = 7.0 for DKC-49–92, N4242BT, and N42B7.

on 31 Dec. 2008. Over the 14 yr there were 13 biomass (at harvest), 13 grain yield (at harvest), 14 ET (crop period), 43 LAI, and 28 d of soil water content measurements available for model calibration.

Simulation RMSEs over the entire cropping system sequence (WCM-M) for soil water storage (180 cm profile), ET, LAI, biomass, and grain yield were 7.5 cm, 4.2 cm, 0.26 $m^2 m^{-2}$, 1518 kg ha^{-1}, and 485 kg ha^{-1}, respectively (Table 5). Corresponding index of agreement (d) values were 0.69, 0.85, 0.96, 0.82, and 0.93 (Table 5). Total profile soil water was not so well simulated (d = 0.69), with overestimations at soil depths <30 cm. However, inspection of the data comparisons presented in Fig. 1 indicates that the model was adequately calibrated for biomass and yield of wheat, corn, and millet in a WCM rotational sequence.

Model Validation

Simulations of the WCM-W and WCM-C Phases

The calibrated model was then evaluated on the remaining two phases of the WCM (WCM-W and WCM-C). The RMSEs of simulated grain yield were 561 and 520 kg ha^{-1}, and that of simulated biomass were 1215 and 891 kg ha^{-1} for the WCM-W and WCM-C phases, respectively (Table 6). Corresponding d values were 0.90 and 0.93 for grain yield, and 0.87 and 0.97 for biomass (Fig. 2 and 3, Table 6). These results are comparable with that for the WCM-M phase in calibration. The RMSEs of soil water, ET, and LAI simulations were between 0.056 and 0.04 $m^3 m^{-3}$, 4.6 to 7.6 cm and 0.58 to 0.64, respectively for the two phases.

Table 4. Cultivar parameters (genetic coefficients) calibrated for simulation of proso millet (cultivar 'Sunup' and 'Huntsman') using the CERES-proso millet module in RZWQM2.

Parameter	Definition	Values used by Saseendran et al. (2009) for 'Sunrise'	Current calibrated values
P1	Thermal time from seedling emergence to the end of the juvenile phase during which the plant is not responsive to changes in photoperiod, GDD†.	40.0	40.0
P20	Critical photoperiod or the longest day length at which development occurs at a maximum rate. At values higher than P20, the rate of development is reduced.	16.5	16.5
P2R	Extent to which phasic development leading to panicle initiation is delayed for each hour increase in photoperiod above P20, GDD†.	20.0	30.0
P5	Thermal time from beginning of grain filling (3–4 d after flowering) to physiological maturity, GDD†.	55.0	155.0
G1	Scaler for relative leaf size.	12.5	1.5
G2	Scaler for partitioning of assimilates to the panicle (head).	7.5	11.5
PHINT	Phyllochron interval; the interval between successive leaf tip appearances, GDD†.	35.0	35.0

† Growing degree days above a base temperature of 10°C.

Table 5. Root mean squared error (RMSE) and index of agreement (d) for comparisons of RZWQM2 simulations of total profile soil water, evapotranspiration (ET), leaf area index (LAI), biomass, and grain yield against measured values in the wheat–corn–millet (WCM-M)† calibration data set at Akron, CO (by crop and for the 14-yr cropping sequence).

Statistic	Crop	Total profile (0–180 cm) soil water	ET	LAI	Biomass	Grain yield
		cm		$m^2\ m^{-2}$	kg ha^{-1}	
Mean	Wheat	23.6	23.5	0.59	2728	848
	Corn	29.1	31.6	0.80	4469	1446
	Millet	29.1	23.4	1.98	4333	1897
	Entire 14-yr cropping sequence	27.3	26.2	1.12	3843	1404
RMSE	Wheat	6.3	2.5	0.27	1616	229
	Corn	10.4	3.1	0.13	1339	469
	Millet	5.6	5.9	0.49	1517	746
	14-yr cropping sequence	7.5	4.2	0.26	1518	485
d	Wheat	0.46	0.89	0.90	0.49	0.77
	Corn	0.58	0.90	0.98	0.63	0.75
	Millet	0.84	0.17	0.90	0.87	0.89
	14-yr cropping sequence	0.69	0.85	0.96	0.82	0.93

† WCM-M = no-till wheat–corn–millet beginning with the millet phase in 1995.

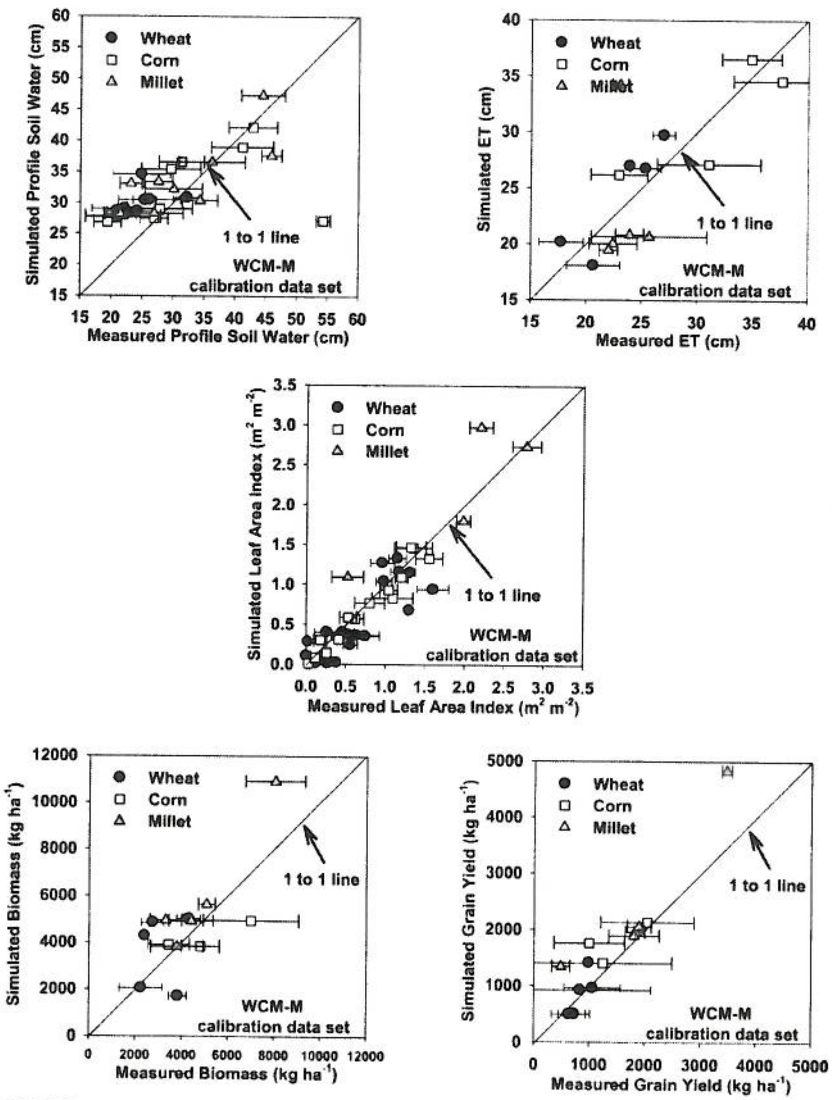

Fig. 1. Comparison of RZWQM2-simulated vs. measured total profile soil water, evapotranspiration, leaf area index, biomass, and grain yield for wheat, corn, and proso millet grown in a wheat–corn–millet rotation at Akron, CO (1995–2008). WCM-M indicates the calibration data set of the wheat–corn–millet rotation beginning with the millet phase in 1995. Error bars indicate one standard deviation from the measured means.

Table 6. Mean or maximum measured values, and root mean squared error (RMSE) and d values in simulations of evapotranspiration (ET), leaf area index (LAI), grain yield, biomass, and soil water in the wheat–fallow (WF), wheat–corn–fallow (WCF), and wheat–corn–millet (WCM).

Cropping system	ET			LAI			Grain yield			Biomass			Total profile, 180 cm soil water		
	Mean	RMSE	d	Max.	RMSE	d	Mean	RMSE	d	Mean	RMSE	d	Mean	RMSE	d
	—— cm ——			— $m^2\ m^{-2}$ —			— kg ha^{-1} —			— kg ha^{-1} —			——— cm ———		
WF-W†	38	9.0	0.87	3.1	0.98	0.33	2046	363	0.80	6783	1803	0.44	32	7.1	0.83
WF-F	46	8.4	0.74	3.0	0.72	0.59	3110	409	0.77	8745	2483	0.88	34	6.6	0.43
WCF-W	42	5.9	0.89	2.7	0.60	0.79	2846	509	0.92	6646	960	0.96	31	6.3	0.65
WCF-C	38	7.3	0.78	3.4	0.96	0.62	2708	470	0.93	6603	1435	0.88	31	6.7	0.57
WCF-F	36	6.9	0.73	3.2	0.76	0.63	2017	587	0.91	5693	1909	0.85	30	6.5	0.50
WCM-W	27	7.4	0.93	2.7	0.64	0.90	1157	561	0.90	3288	1215	0.87	26	7.9	0.65
WCM-C	29	7.6	0.89	2.8	0.86	0.85	2014	520	0.93	4425	891	0.97	32	7.4	0.63
WCM-M	26	4.2	0.85	2.9	0.26	0.96	1389	485	0.93	3747	1518	0.82	29	7.5	0.69

† WF–W (beginning with the wheat phase in 1992), WF–F (beginning with the fallow phase in 1992), WCF–W (beginning with the wheat phase in 1992), WCF–C (beginning with the corn phase in 1992), WCF–F (beginning with the fallow phase in 1992), WCM–W (beginning with the wheat phase in 1995), WCM–C (beginning with the corn phase in 1995), and WCM–M (beginning with the millet phase in 1995).

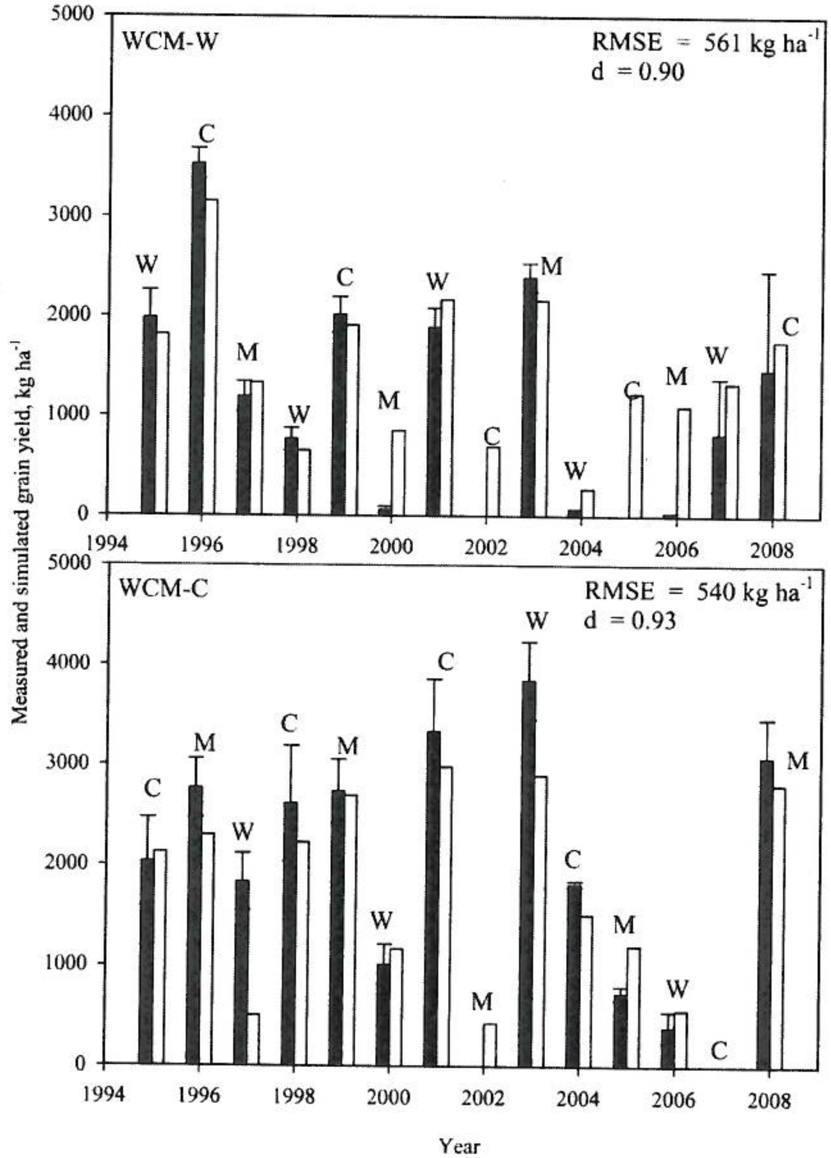

Fig. 2. Comparison of measured (solid bars with error bars) and simulated (open bars without error bars) grain yield for wheat, corn and millet grown in the wheat–corn–millet rotation beginning with the wheat phase in 1995 (WCM-W) and beginning with the corn phase in 1995 (WCM-C). The error bars indicate one standard deviation of measured means. RMSE = root mean squared error and d = index of agreement.

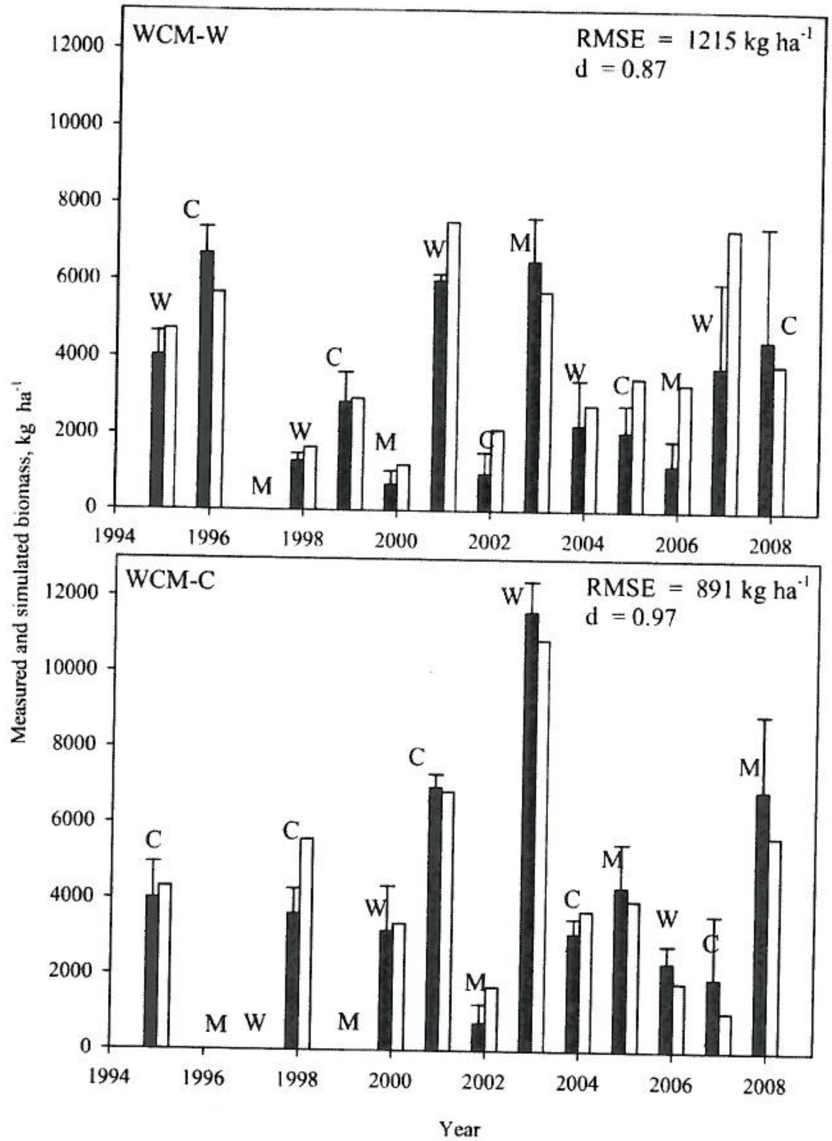

Fig. 3. Comparison of measured (solid bars with error bars) and simulated (open bars without error bars) biomass for wheat, corn and millet grown in the wheat–corn–millet rotation beginning with the wheat phase in 1995 (WCM-W) and beginning with the corn phase in 1995 (WCM-C). The error bars indicate one standard deviation of measured means. RMSE = root mean squared error and d = index of agreement.

In the WCM-W, notwithstanding the high spatial variability exhibited in crop performance in the experiments as reflected in the high SDs of the measured mean, 10 out of 14 grain yield simulations (5 out of 5 for wheat, 3 out of 5 for corn, and 2 out of 4 for millet crops) corresponded well with the measured yields (Fig. 2). In 2000 and 2006, there were overestimations of millet yield (983 kg ha^{-1} vs. the measured 62 kg ha^{-1} in 2000, and 1235 kg ha^{-1} vs. the measured 16 kg ha^{-1} in 2006). Although the model simulated average water stresses of 0.48 (0 = no stress and 1 = severe stress) during the anthesis stage, 0.70 during panicle growth stage, and 0.43 during the maturity period in 2000, and 0.36 during leaf growth period, 0.51 during anthesis to panicle growth period, and 0.70 during the panicle to maturity periods in 2006, the model still simulated sizable yield in both years compared to the near crop failure in the field. Thus, there is a need to improve model response to very severe drought conditions. Although the model predicted the decline in corn grain yields in 2002 and 2005 at 586 kg ha^{-1} and 829 kg ha^{-1}, respectively (Fig. 2), the severe drought caused crop failure in these 2 yr in the WCM-W phase. The model simulated a water stress of only 0.5 during silking to grain filling in 2002 and only 0.3 in 2005. Obviously, the simulated stresses were not enough to cause a crop failure. However, the harvested biomass reported in those years were simulated well within one SD of the measured mean (Fig. 3), which indicates that the model needs improvement on estimating the effects of stress during pollination and partitioning of photosynthate to simulate yield correctly in 2000, 2002, 2005, and 2006. In general, the biomass of the crops in the rotation was adequately simulated, with 11 out of 13 simulated biomasses within 1 SD of the measured means.

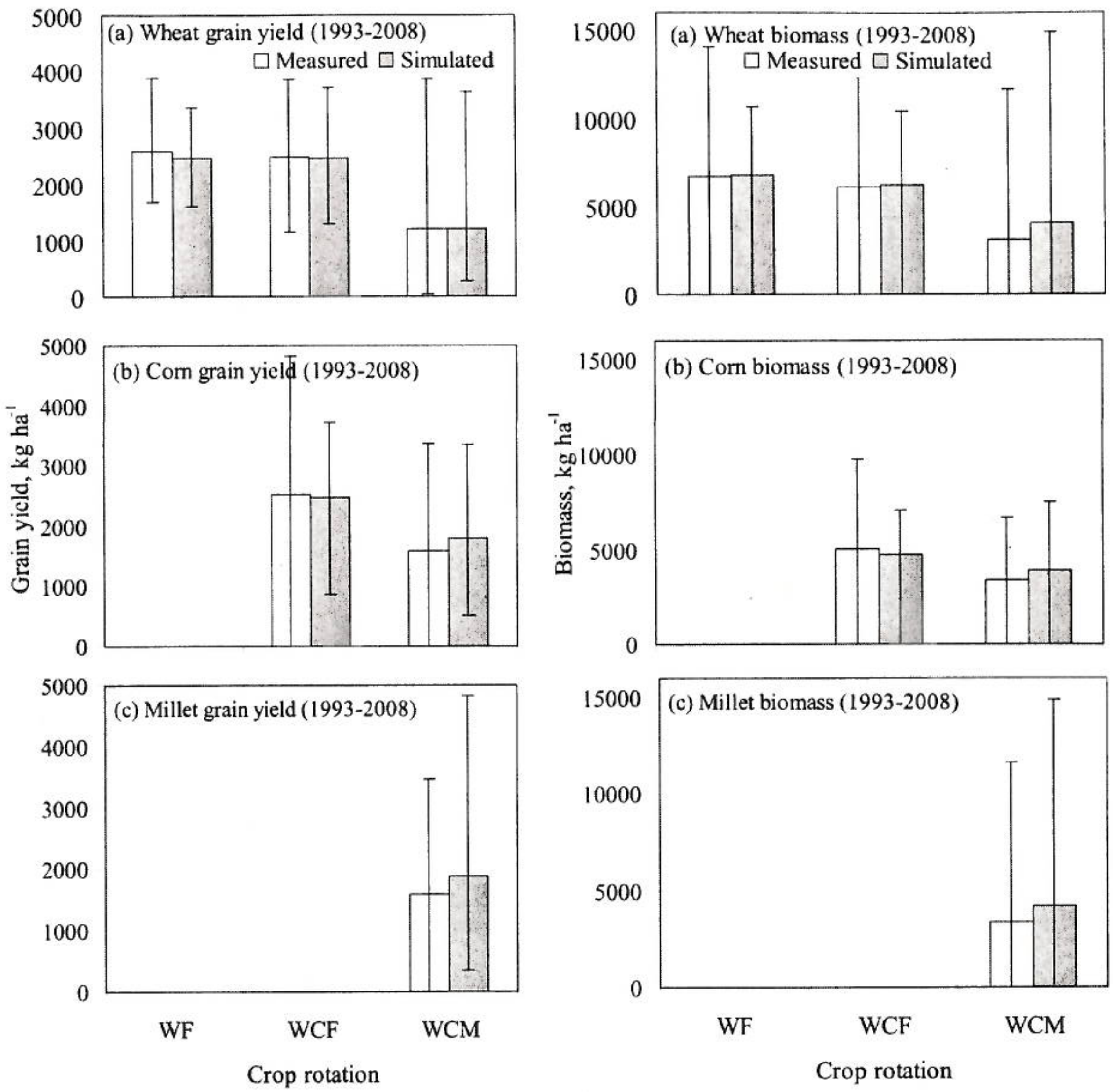

Fig. 4. Average (1993–2008) wheat, corn, and proso millet grain yields as observed at Akron, CO and simulated by RZWQM2 in wheat–fallow (WF), wheat–corn–fallow (WCF), and wheat–corn–millet (WCM) crop rotations. Ends of the bars indicate maximum and minimum observed and simulated yield and biomass.

With the exception of the wheat grain yield in 1997, all the biomass and grain yields in the WCM-C were simulated well with an RMSE of 540 kg ha^{-1} and d value of 0.93 for grain yield, and an RMSE of 891 kg ha^{-1}, and d value of 0.97 for biomass (Fig. 2 and 3). In 1997, the water stress (average 0.5) simulated during the early vegetative stage of wheat slowed LAI development drastically, resulting in low LAI and poor grain yield at harvest, but there were no LAI and biomass measurements this year to compare with. Probably the model overestimated the stress effects on LAI that year resulting in the large errors in grain yield simulated. In the severe drought year of 2002, no harvestable millet grain yield was reported (0 kg ha^{-1}), and the model simulated a grain yield of 529 kg ha^{-1} which did reflect a sharp decline in yield compared with the millet yields in the preceding and succeeding years (e.g., measured millet yield in 1999 was 2735 kg ha^{-1} that was predicted well).

Overall the simulated means and ranges of grain yields for all three crops in all three phases of WCM corresponded closely to observed means and ranges (Fig. 4). Simulated mean wheat yield and biomass were 101 and 125% of their observed means, respectively. The model correctly simulated the decreased mean wheat yield observed for wheat grown after millet without a fallow period (WCM) compared with wheat after fallow (the two other systems) (Fig. 4). Simulated mean corn yield was 113% of the observed mean. The model also correctly simulated the decreased mean corn yield observed in the more intensively cropped WCM system. Simulated mean millet yield and biomass were within 125% of the observed mean. The simulated yield and biomass ranges for all three crops were generally less than the observed ranges (85% averaged over all crops and systems).

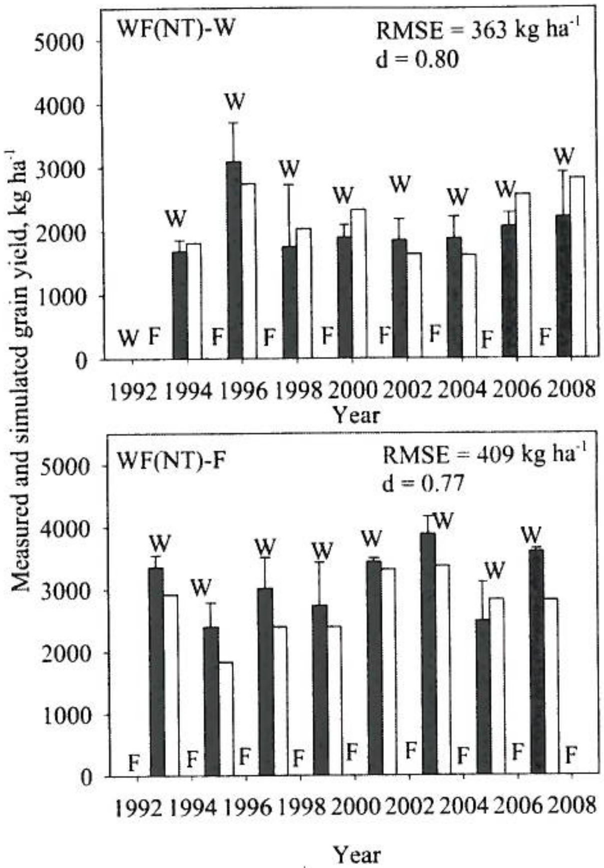

Fig. 5. Measured (solid bars with error bars) and simulated (open bars without error bars) winter wheat yield in the wheat–fallow with wheat phase in 1992 (WF-W) and wheat–fallow with fallow phase in 1992 (WF-F). The error bars indicate one SD of measured means. RMSE = root mean squared error, SD = standard deviation, and d = index of agreement.

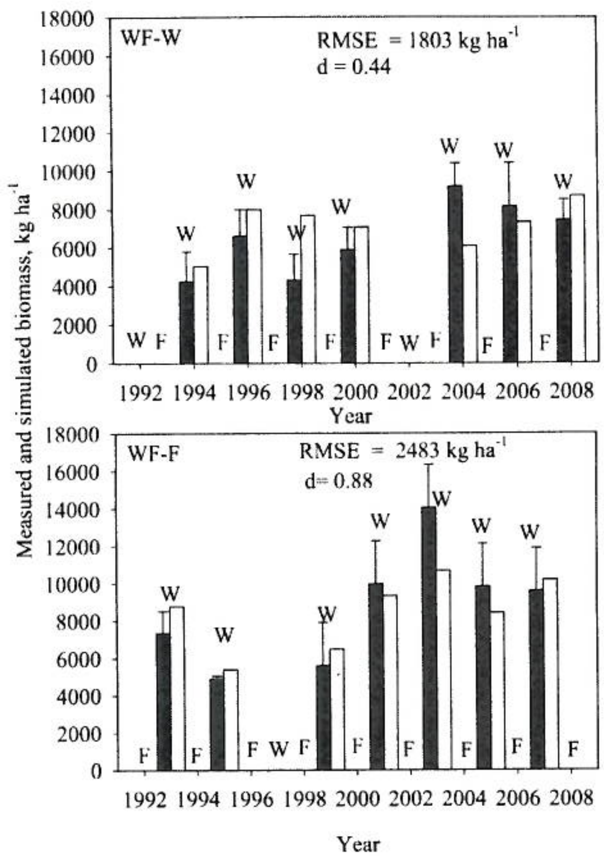

Fig. 6. Measured (solid bars with error bars) and simulated (open bars without error bars) winter wheat biomass in the wheat–fallow with wheat phase in 1992 (WF-W) and wheat–fallow with fallow phase in 1992 (WF-F). The error bars indicate one SD of measured means. RMSE = root mean squared error, SD = standard deviation, and d = index of agreement.

Simulations of the Wheat–Fallow and Wheat–Corn–Fallow Rotations

We further evaluated the calibrated model on WF and WCF in terms of biomass, grain yield, ET, LAI, and soil water simulations (Fig. 5–8) with major emphasis on biomass and grain yield. Simulated wheat grain yield and biomass in the WF (both W and F phases combined) had RMSEs of 444 (d = 0.87) and 2547 (d = 0.70) kg ha^{-1}, respectively (Table 6). Out of the 16 crop seasons simulated in the WF systems, eight grain yield simulations were within 1 SD of the measured means (Fig. 5). The deviations of an additional seven simulations were also reasonably close to the measured values. In the remaining crop season (2007) under WF–F, simulations deviated from the measured considerably. In this crop season, the model simulated 2712 kg ha^{-1} compared with the measured value of 3599 kg ha^{-1}. The model simulated a water stress factor of 0.49 during the ear growth period causing the grain yield to decline more than measured. Precipitation of 178 mm was recorded during the crop season but mainly from a few high intensity storms. During the season, there were three noticeable storms on 24 March, 24 April, and 12 June with precipitation 13, 36, and 32 mm. The model simulated no runoff in response to the 13 mm precipitation on 24 March. However, the 36 and 32 mm precipitations on 24 April and 12 June generated 11 and 15 mm runoff. This simulated runoff was likely a result of our assumption of 120-min storm durations used to create the breakpoint precipitation data required for the model. These two storms actually occurred over periods of 19 h (24 April) and 11 h (12 June), and likely did not generate the amounts of runoff simulated by the model, resulting in the greater water availability and greater observed yields compared with simulated yields. Biomass simulations were less accurate compared with grain yield simulations (Table 6 and Fig. 6), but they were comparable to results from an earlier study of the WF and WCF data from 1992 to 2002 by Saseendran et al. (2005a).

Grain yields (wheat and corn data combined) in the WCF-W were simulated well with RMSE of 509 kg ha^{-1} and d of 0.91 (Fig. 7). Out of the 11 crop seasons simulated, eight were within one SD of the measured means. Even though the absolute amount of simulated corn yield in 1999 and 2008 deviated from the measured by more than one SD, trends in yield variation in these years were adequately captured and the absolute deviations from the measured were not large. However, wheat grain yield simulation in 2007 deviated from the measured by 1025 kg ha^{-1} (error of −29%). During this crop season, the model was not able to simulate the soil water dynamics well, leading to a high water stress (0.58) during early ear development resulting in underprediction of grain yield. Biomass

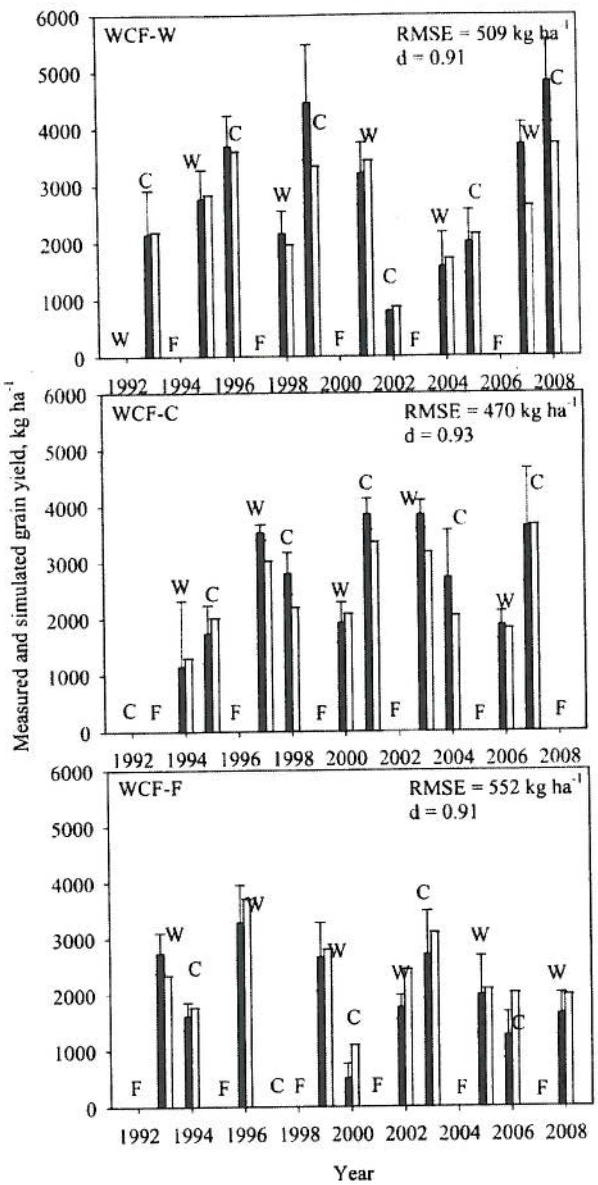

Fig. 7. Measured (solid bars with error bars) and simulated (open bars without error bars) winter wheat, corn, and proso millet grain yields in the wheat–corn–fallow with wheat phase in 1992 (WCF-W), wheat–corn–fallow with corn phase in 1992 (WCF-C), and wheat–corn–fallow with fallow phase in 1992 (WCF-F). The error bars indicate one SD of measured means. RMSE = root mean squared error, SD = standard deviation, and d = index of agreement.

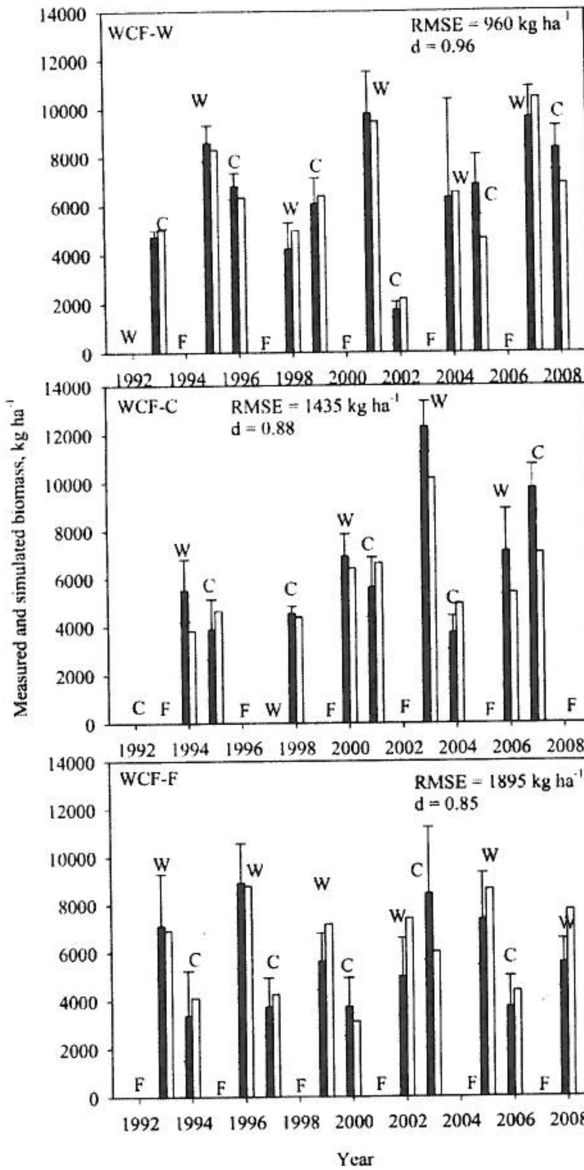

Fig. 8. Measured (solid bars with error bars) and simulated (open bars without error bars) winter wheat, corn, and proso millet biomass in the wheat–corn–fallow with wheat phase in 1992 (WCF-W), wheat–corn–fallow with corn phase in 1992 (WCF-C), and wheat–corn–fallow with fallow phase in 1992 (WCF-F). The error bars indicate one SD of measured means. RMSE = root mean squared error, SD = standard deviation, and d = index of agreement.

(wheat and corn together) simulations in the WCF–W were reasonably accurate with RMSE of 960 kg ha^{-1} and d value of 0.96 (Fig. 8). The RMSEs of simulations of ET, LAI, and soil water at various depths were 5.9 cm, 0.60, and 0.061 m^3 m^{-3}.

Wheat and corn grain yields in the WCF–C were also simulated with reasonable degree of accuracy, with RMSE of 470 kg ha^{-1} and d value 0.93 (Fig. 7). With the exception of the wheat crop in 1997 and corn in 2001 (both were undersimulated), all measured crop yields were predicted within two SDs of the measured means, with six of the simulations within one SD. Deviation of simulations from the measured was −15% in 1997 and −13% in 2001. The measured wheat yield in 1997 was 3535 kg ha^{-1} with a SD of only 139 kg ha^{-1} of the measured mean. In the case of corn in 2001, the model simulated on average water stress of 0.41 during the grain filling period causing the yield reduction that was not observed in the field. However, the simulated yield in general was well correlated with the measurements and yearly variability with high prediction accuracy (d). Combined wheat and corn biomass in the WCF–C were simulated well, with RMSE of 1435 kg ha^{-1} and d value of 0.88 (data not shown). Out of the nine biomass measurements available for comparison, five of the simulations were within one SD and the remaining four simulations were within two SDs of the measured means. The RMSEs of simulations of ET, LAI, and soil water at various depths were 7.3 cm, 0.96, and 0.064 m^3 m^{-3} (data not shown).

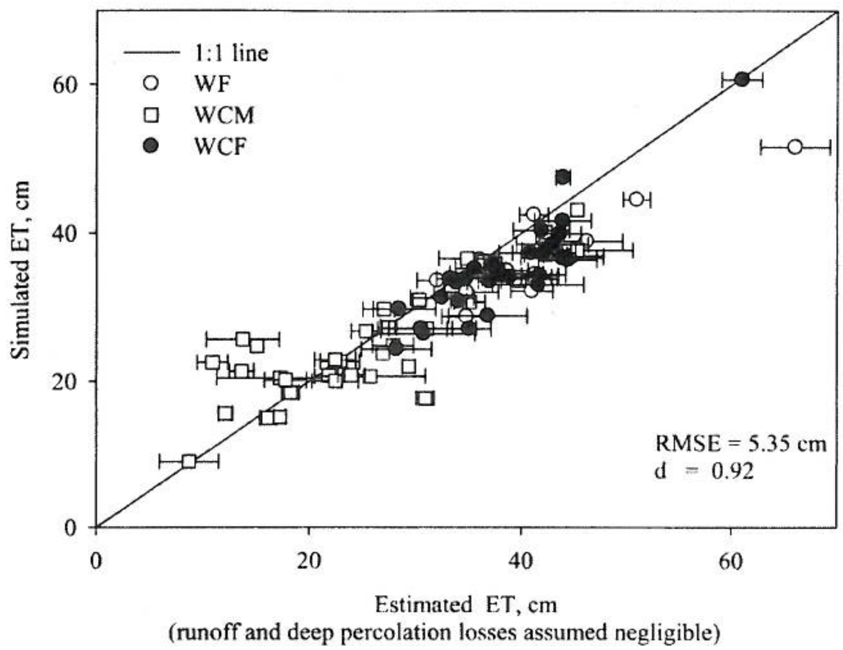

Fig. 9. Measured and simulated crop (winter wheat, corn, and proso millet) evapotranspiration (ET) under wheat–fallow (WF), wheat–corn–fallow (WCF), and wheat–corn–millet (WCM). The error bars indicate one SD of measured means. RMSE = root mean squared error, SD = standard deviation, and d = index of agreement.

Compared with measured yield from the WCF–W and WCF–C phases, the measured grain yield and biomass of both wheat and corn in the WCF–F phase were low and showed high degree of variability as reflected in the SDs (Fig. 7 and 8). Corn grain yield from 1997 was removed from the analysis (as discussed in the case of WCM–M above) because of hail damage. Simulated grain yield in this phase was reasonably accurate with RMSE of 552 kg ha^{-1} and d value of 0.91. Six out of the 10 simulated grain yields were within one SD of the measured means. In 2000 and 2006, the simulations deviated by less than two SDs of the measured means. In 2000, low LAI was simulated even though no appreciable water stress was simulated. For instance, on 23 May 2000, the model simulated an LAI of 1.12 against the measured value of 2.93. In the CERES-maize model, calculation of LAI was based on leaf number and plant population, and we did not have measurements of leaf number in the experiments to investigate further to ascertain if the leaf number or plant population simulation or LAI calculation in the model failed during this season. In 2006, there was a drastic drop in measured corn grain yield due to the low growing season precipitation and very dry early season conditions (94 mm during March to June, with only 18 mm during the entire month of June), which was not captured by the model. Biomass simulations in the WCF–F corresponded reasonably well with the measurements, with 8 out of the 11 measured values within one SD of the means, and the remaining three simulations were within two SDs (Fig. 8). The RMSEs of biomass, ET, LAI, and soil water at various depths were 1895 kg ha^{-1}, 6.9 cm, 0.76, and 0.069 $m^3 m^{-3}$ (Fig. 8).

Overall, simulated grain yield and biomass in the WCF corresponded well with the field measurements (Fig. 7 and 8, and Table 6). The RMSE and d values of simulated grain yield were 432 kg ha^{-1} and 0.91 for wheat, and 607 kg ha^{-1} and 0.93 for corn (Table 6), and corresponding statistics for biomass were 1854 kg ha^{-1} and 0.79 for wheat, and 1551 kg ha^{-1} and 0.79 for corn. Moreover, yield responses of both wheat and corn to weather change and crop rotation sequences were well simulated during the experimental period (Fig. 7 and 8).

Simulated means and ranges of grain yield for both wheat and corn corresponded closely to observed means and ranges of yields over the experimental period (Fig. 4). Simulated mean wheat yields were 95 and 99% of the observed mean, and simulated wheat biomass were 102 and 102% of the observed mean for the WF and WCF rotations, respectively. Simulated mean corn yield was 98% of the observed mean and simulated biomass was 95% of the observed mean for the WCF. The simulated yield and biomass ranges for all wheat and corn were generally less than the observed ranges (85% averaged over the two crops), but were adequate to provide valuable information to farmers regarding potential production variability and risk that might be experienced for each of the cropping systems evaluated. The simulations of ET for all three crops in all three rotations were well correlated with measured ET (Fig. 9) over a large range, but with a tendency to underestimate ET (RMSE of 5.35 cm and d value of 0.92).

Projected Wheat–Millet–Fallow and Wheat–Corn–Millet–Fallow Rotations

After calibration and evaluation, the model was then used to "construct" two more rotations using the three crops: WMF and WCMF. The WMF and WCMF rotations for 1993–2008 crop seasons were constructed using the individual crop management information available for wheat, corn, and millet crops used in the WF, WCF, and WCM rotations described above. Although field experiments were conducted at the location for the WMF and WCMF, field data were withheld from the modelers and only used to confirm the simulation results.

The simulation results indicated the usefulness of the model to give reasonable estimates of mean and ranges of grain yields. The least accurate mean yield and biomass simulations were seen for wheat in the WMF rotation, where mean yield and biomass were overpredicted by 39% and 31%, respectively (Fig. 10). However, mean wheat yield was accurately predicted for the WCMF rotation (yield overpredicted by 72 kg ha^{-1}, 3%). Simulated mean corn yields were underpredicted by 285 kg ha^{-1} (13%) in the WCMF system. Simulated mean millet yields were predicted within 74 kg ha^{-1} (5%) in both the WMF and WCMF systems. Simulated ranges for wheat and millet grain yield and biomass were similar to observed ranges. The model greatly underestimated the range of corn biomass and grain yield in the WCMF rotation, in part because the

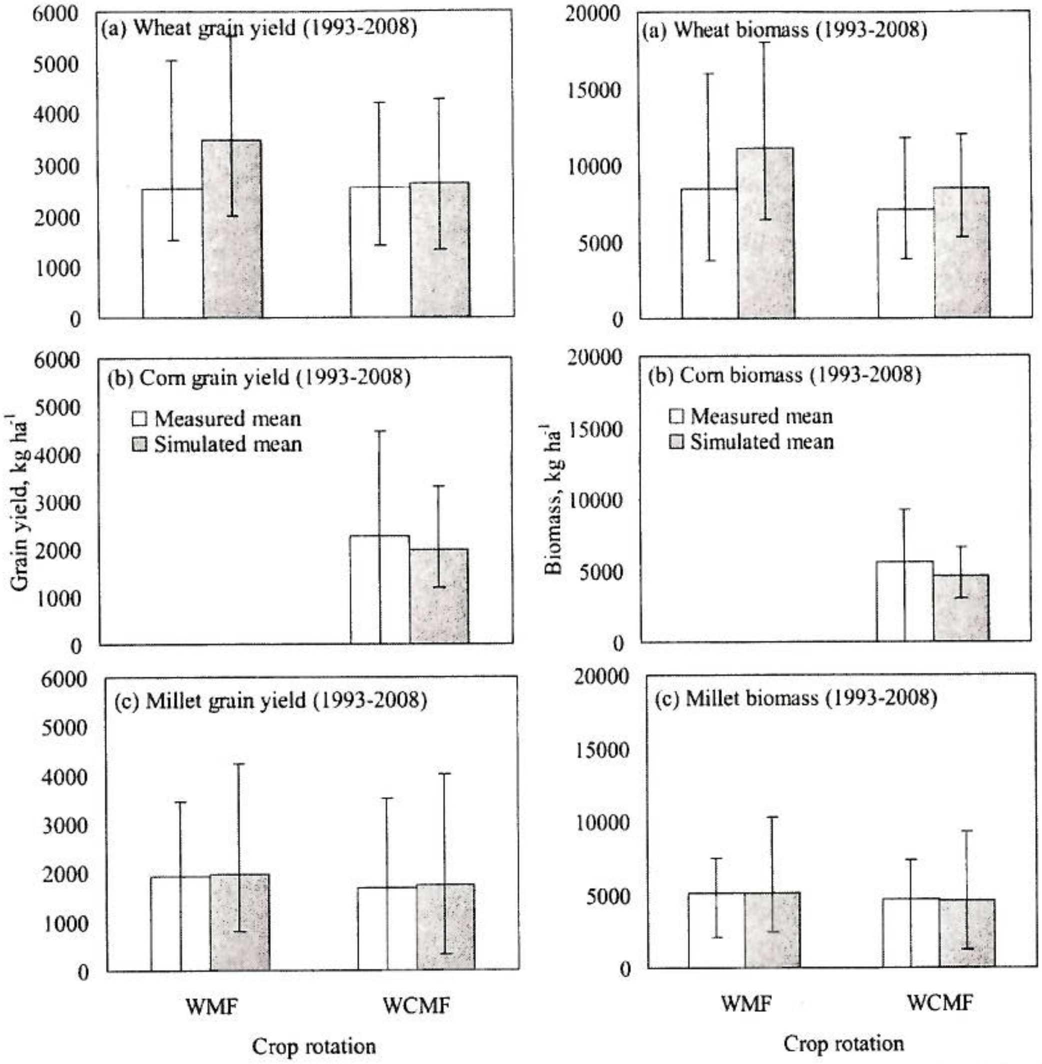

Fig. 10. Average (1993–2008) wheat, corn, and proso millet grain yields and biomass as observed at Akron, CO and simulated by RZWQM2 in wheat–millet–fallow (WMF) and wheat–corn–millet–fallow (WCMF) crop rotations. Ends of the bars indicate maximum and minimum observed and simulated yield and biomass.

model did not correctly simulate the zero yield obtained during the severe drought year of 2002.

Precipitation Use Efficiency and Water Use Efficiency of All Crop Rotations

Precipitation use efficiency (PUE) and water use efficiency (WUE) were defined as total yield of all crops divided by total precipitation or total water use for a certain period of time. For estimation and comparison of PUE and WUE of the WF, WCF, WMF, WCM, and WCMF rotations, precipitation, crop ET, and crop yield data from 1996 to 2008 were used when all rotations had completed their respective cycles. In general, the simulated WUEs and PUEs corresponded well with the measured values (Table 7). Simulated PUE ranged from 3.68 kg ha^{-1} mm^{-1} for WF to 4.76 kg ha^{-1} mm^{-1} for WCF, and corresponded well with measured values of 3.79 kg ha^{-1} mm^{-1} for WF and 4.90 kg ha^{-1} mm^{-1} for WCF (Table 7). Highest measured and simulated WUEs were obtained for the WCM (6.34 and 5.85 kg ha^{-1} mm^{-1}) but the highest PUE was for the WCF in both simulated and measured results. However, in both measurements and simulations, the rotation with the lowest values for both WUE and PUE was WF.

CONCLUSIONS

In this study, we tested a cropping systems model, RZWQM2, for its ability to effectively simulate sequential yield and biomass production, and WUE and PUE in

Table 7. Precipitation use efficiency (PUE) and water use efficiency (WUE) of wheat–fallow (WF), wheat–corn–fallow (WCF), wheat–corn–millet (WCM) and wheat–corn–millet–fallow (WCMF) rotations for the period 1996 to 2008.

Crop rotation	PUE		WUE	
	Measured	Simulated	Measured	Simulated
	kg ha^{-1} mm^{-1}			
WF	3.79	3.68	3.23	3.13
WCF	4.90	4.76	4.64	4.51
WCM	3.99	4.28	5.85	6.34
WMF	4.18	4.05	4.01	3.89
WCMF	4.49	4.24	4.27	4.03

alternative crop rotations involving wheat, corn, millet, and fallow under no-till management at Akron, CO from 1993 to 2008. The model was adequately calibrated for total soil profile water, ET, LAI, biomass, and grain yield using data from one phase of a WCM rotation. The model effectively simulated the long-term (1993–2008) average and range of yield for winter wheat, corn, and proso millet in the WF, WCF, and WCM cropping systems with varying cropping intensity. Additionally, without further calibration the model adequately predicted average wheat, corn, and millet yields in two additional rotations (WMF, WCMF). Long-term WUE and PUE of all the crop rotations were simulated adequately. The results of this study indicated that the RZWQM2 model is capable of simulating sequential crop rotation effects in the Central Great Plains and may be used as a potential tool to develop decision support aids for crop sequence selection based on limited field experiments.

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