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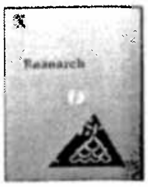

Modeling responses of dryland spring triticale, proso millet and foxtail millet to initial soil water in the High Plains

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ABSTRACT

Dryland farming strategies in the High Plains must make efficient use of limited and variable precipitation and stored water in the soil profile for stable and sustainable farm productivity. Current research efforts focus on replacing summer fallow in the region with more profitable and environmentally sustainable spring and summer crops. In the absence of reliable precipitation forecasts for the crop growing season, farmers rely mainly upon knowledge of plant available water (PAW) in the soil profile at planting for making crop choice decisions. To develop a decision support strategy for crop selection based on initial PAW, experiments were conducted with spring triticale (*X Titicosecale* Wittmack), proso millet (*Panicum miliaceum* L.), and foxtail millet (*Setaria italica* L. Beauv.) under artificially controlled Low, Medium, and High initial PAW levels during 2004 and 2005 at Akron, Colorado, and Sidney, Nebraska. The objectives of this study were to adapt an existing cropping systems model for the simulation of triticale and millet and to evaluate simulations from the adapted model by comparing results with field data collected under varying initial PAW conditions. The Root Zone Water Quality Model with DSSAT v4.0 crop growth modules (RZWQM2) was used. Specifically, the Cropping System Model (CSM)–CERES–Wheat module was adapted for simulating triticale, and CSM–CERES–Sorghum (v4.0) module was adapted for simulating proso millet and foxtail millet. Soil water, leaf area index, grain yield, and biomass data for the highest PAW treatment from one crop season for each of the three crops were used to adapt and calibrate the crop modules. The models were then evaluated with data from the remaining PAW treatments. The proso millet module was further tested with four years of data from a crop rotation experiment at Akron from 2003 to 2006. Simulation results indicated that the adapted and calibrated crop modules have the potential to simulate these new crops under a range of varying water availability conditions. Consequently, these models can aid in the development of decision support tools for the season-to-season management of these summer fallow replacement crops under dryland conditions in semi-arid environments.

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1. Introduction

Profit margins for the production of most rainfed crops in the semi-arid climate of the Great Plains of the USA are very small (Clarke and Rendell, 2003; DeVuyst and Halvorson, 2004; Dhuyvetter et al., 1996; Meko and Woodhouse, 2005) due to frequent and extended episodes of severe drought. Farmers in the semi-arid Great Plains have traditionally used long periods of fallow in a wheat (*Triticum aestivum* L.)-fallow cropping system to conserve soil water for the wheat crop and to stabilize production. The fallow system relies on the principle that leaving the land bare over a period of time allows water to accumulate in the soil. While this practice does indeed help stabilize crop yield, more intensified cropping systems, made possible with no-tillage practices that conserve residue cover, have been found to be more beneficial in terms of their increased precipitation storage efficiency, production, soil carbon sequestration, and decreased water and wind erosion potentials (Farahani et al., 1998; Halvorson et al., 2002a,b; Lal et al., 1998; Nielsen and Aiken, 1998; Nielsen et al., 2005; Peterson et al., 1998; Peterson and Westfall, 2004). Efforts are

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Table 1
Plant available water (PAW) in the upper 120 cm of the soil profile prior to planting for spring triticale, proso millet, and foxtail millet at Sidney, NE and Akron, CO.

Location	Year	Spring triticale (mm)			Proso millet (mm)[a]			Foxtail millet (mm)[a]		
		Low	Medium	High	Low	Medium	High	Low	Medium	High
Sidney	2004	35	66	134	–	–	–	–	–	–
	2005	134	154	174	212	228	244	212	228	244
Akron	2004	64	127	168	90	140	190	98	132	161
	2005	98	144	199	–	–	–	–	–	–

[a] Foxtail and proso millet were lost to hail at Sidney in 2004, and soil crusting prevented emergence at Akron in 2005.

Table 2
Planting/harvest dates for spring triticale, proso millet and foxtail millet at Sidney, NE and Akron, CO.

Location	Year	Spring triticale	Foxtail millet	Proso millet
Sidney	2004	Apr 6/Jun 23	–	–
	2005	Apr 7/Jun 24	Jun 8/Aug 16	Jun 8/Aug 30
Akron	2004	Apr 7/Jun 23	Jun 2/Aug 26,30[a]	Jun 2/Aug 30
	2005	Apr 4/Jun 24	–	–

[a] At Akron in 2004, foxtail millet plots receiving the high level of supplemental water were harvested on August 26 as a result of more rapid crop development. The remaining foxtail millet plots were harvested on August 30.

successful for spring triticale in 2005 at Akron where the High treatment had 101 mm more PAW than the Low treatment. A smaller range in available soil water at planting was established at Sidney in 2005 for the three crops as a result of above normal precipitation.

Nutrient needs were based on regional recommendations. No supplemental fertilizer was applied in either year at Sidney. At Akron, 67.2 kg N ha^{-1} was applied on the surface beside each row and 22.4 kg ha^{-1} P_2O_5 was applied in the row at planting for spring triticale, foxtail millet, and proso millet in both years.

All crops were no-till seeded into corn stubble. Row spacing was 25 cm at Sidney and 19 cm at Akron. Planting dates are shown in Table 2. Spring triticale 'Trical 2700' was sown at 101 kg seed ha^{-1}. 'White Wonder' foxtail millet and 'Sunrise' proso millet were sown at 17 kg seed ha^{-1}. Proso and foxtail millet crops were lost to hail in late July at Sidney in 2004. Establishment of these crops was unsuccessful at Akron in 2005 due to soil crusting and subsequent dry surface soil conditions. Weeds were controlled by hand-weeding during the cropping season and glyphosate [N-(phosphonomethyl) glycine] was used during non-crop periods.

Leaf area index (LAI) and dry matter measurements were made a minimum of three times throughout each growing season. Leaf area index was estimated using a plant canopy analyzer (LAI-2000, LI-COR, Lincoln, NE, USA) with the 270° view restrictor to mask the operator (i.e., 270° open, 90° masked). One measurement above and four below the canopy were taken twice in each plot to

Table 3
Measured (M) and simulated (S) phenology for spring triticale, proso millet, and foxtail millet grown at Sidney, NE and Akron, CO.

Location	Year	Triticale			Proso millet			Foxtail millet		
			DAP			DAP			DAP	
		Stage	M	S	Stage	M	S	Stage	M	S
Sidney	2004	Planting (Apr 6)								
		Emergence	13	12						
		Boot swollen	65							
		Head visible	70							
Sidney	2005	Planting (Apr 7)			Planting (June 8)			Planting (June 8)	0	
		Emergence	18	12	Emergence	5	7	Emergence	5	7
		Head visible	75		Head visible	49		Head visible	57	
					Head fully emerged	64		Head fully emerged	68	
Akron	2004	Planting (Apr 7)			Planting (June 2)	0		Planting (June 2)	0	
		Emergence	12	11	Emergence	10	10	Emergence	10	8
		Jointing	53		Head visible	50		Flag leaf visible	58	
		Awns visible	68		Head fully emerged	64		Head visible	75[a]	
		Anthesis	77	69	Anthesis	70	77	50% headed	85[a]	
					Early dough	79				
					Phys. Mat.	89	93			
Akron	2005	Planting (Apr 4)								
		Emergence	10	12						
		Jointing	60							
		Boot swollen	70							
		Head fully emerged	76							
Akron	2004				Planting (June 7)					
					Emergence	15	15			
Akron	2005				Planting (June 10)					
					Emergence	7	11			
Akron	2006				Planting (June 8)					
					Emergence	19	13			

DAP = days after planting.

[a] These data apply only to the High water treatment. The Low water treatment did not progress beyond the "flag leaf visible" stage, and the Medium treatment had just a few heads visible at harvest (85 DAP).

2.2.1. Species and ecotype parameters for triticale

Much less literature exists on the growth and development characteristics of spring triticale compared with information for its parental lines [wheat and rye (*Secale cereale* L.)] that can be directly used for developing crop specific parameters for simulation of the crop. However, Ewert et al. (1996) successfully simulated phenological development in winter triticale using a wheat crop simulation model (AFRCWHEAT2), although they acknowledged that progress in simulating the development of cereals is limited by lack of knowledge about plant physiology. Singer et al. (2007) reported radiation use efficiencies of winter triticale in the range of $2.84–3.28\ \mathrm{g\ MJ^{-1}}$ across various plant densities (67–170 plants $\mathrm{m^{-2}}$). We used a constant calibrated value of $2.7\ \mathrm{g\ MJ^{-1}}$ 1 for RUE in the simulations (an ecotype parameter in the CERES-Wheat module). For simulation of spring triticale, a value of 0.65 for PAR extinction coefficient was found to give the best results. To calculate growing degree days (GDD) we used a uniform base temperature of 0 °C for all growth stages of the crop (Gallagher, 1979), similar to wheat. However, we used a base temperature of 5 °C for accumulation of GDD during grain filling as it improved the simulations. Based on the above information in the literature and through calibration, a new ecotype parameter set was developed for the simulations of spring triticale (Table 4). The species parameter set for wheat was used to simulate triticale after adjusting four of the parameters to the values shown in Table 5.

2.2.2. Species and ecotype parameters for proso and foxtail millets

Proso millet and foxtail millet are short-season summer annual small cereal crops with high water-use efficiency (C4 plants) and are well adapted to crop production systems in the semi-arid environment of the USA (Lyon and Baltensperger, 1993; Anderson, 1994). Information on detailed growth and development characteristics of the two millets is lacking in the literature. There have been only limited efforts reported to model these crop species in the past. In order to simulate cropping sequences that involved proso millet in the Great Plains, Andales et al. (2003) simulated proso millet by parameterizing a generic crop model (EPIC; Williams et al., 1989) available in the GPFARM farming system model by making best guess estimates for the generic crop simulation model parameters. In RZWQM2-DSSAT v4.0, crop modules are available for sorghum (CSM-CERES-Sorghum) and pearl millet (*Pennisetum americanum* L.) (CSM-CERES-Millet) that fall broadly in the millet family. We experimented with both the modules for modeling the proso and foxtail millets and found the CSM-CERES-Sorghum module better suited for simulation of the millets (results not presented). Anderson (1994) showed that proso millet development can be related to temperature by using GDD calculated with a base temperature of 10 °C. For simulation of both proso and foxtail millet crops we adopted this base temperature as it worked well for quantifying the effects of temperature on both photosynthesis and grain filling processes. Based on the available information in the literature and calibration, a new ecotype parameter set was developed for the simulations (Table 6). In addition to modifying the species and ecotype parameter files, we also made changes to the CSM-CERES-Sorghum v4.0 module. Growing degree days from germination to emergence (P9) is not calculated by CSM-CERES-Sorghum v4.0, but we calculated P9 using the relationship from CERES-Maize as

$$P9 = 45.0 + GDDE \times SDEPTH \tag{1}$$

where GDDE (an ecotype parameter) is GDD per cm seed depth (SDEPTH) required for emergence.

In order to better match the simulated pattern of leaf area development with the observed pattern, the equation used for calculation of leaf senescence during crop development stage 3 (SLAN) was modified to

$$SLAN = 1 + 50\left(\frac{SUMDTT}{P3}\right)^2 \tag{2}$$

where SUMDTT is GDDE accumulated starting from seedling emergence, P3 is the duration of the development phase from end of leaf growth to end of spike growth, and stage 3 is the period from panicle initiation to end of leaf growth.

Table 8

Cultivar parameters (genetic coefficients) calibrated for simulation of triticale (cv. Trical 2700) using the CSM-CERES-Wheat module.

No.	Acronym/Parameter	Value
1	P1V/Relative amount that development is slowed for each day of unfulfilled vernalization, assuming that 50 days of vernalization is sufficient for all cultivars, GDD	5
2	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), GDD	105
3	P5/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	450
4	G1/Kernel number per unit weight of stem (less leaf blades and sheaths) plus spike at anthesis, 1/g	30
5	G2/Kernel filling rate under optimum conditions, mg/day	35
6	G3/Non-stressed dry weight of a single stem (excluding leaf blades and sheaths) and spike when elongation ceases, g	1
7	PHINT/Phyllochron interval, GDD	60

Table 9

Cultivar parameters (genetic coefficients) calibrated for simulation of proso millet (cv. Sunrise) and foxtail millet (cv. White Wonder) using the CSM-CERES-Sorghum module.

No.	Acronym/Parameter	Value	
		Proso millet	Foxtail millet
1	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[a]	40.0	220
2	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, hours	16.5	12.5
3	P2R/Extent to which phasic development leading to panicle initiation is delayed for each hour increase in photoperiod above P20, GDD[a]	20.0	40.0
4	P5/Thermal time from beginning of grain filling (3–4 days after flowering) to physiological maturity, GDD[a]	55.0	10.0
5	G1/Scaler for relative leaf size	12.5	0.0
6	G2/Scaler for partitioning of assimilates to the panicle (head)	7.5	0.0
7	PHINT/Phyllochron interval; the interval between successive leaf tip appearances, GDD[a]	35.0	56.0

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

the average deviation between simulated and observed values; (ii) Mean Relative Error (MRE), Eq. (4), which gives the bias of the simulated value relative to the observed value; and (iii) the index of agreement (d), Eq. (5) between measured and simulated parameters (Willmott, 1981), which varies between 0 (poor model) and 1 (perfect model):

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \tag{3}$$

$$\mathrm{MRE} = \frac{1}{n}\sum_{i=1}^{n}\mathrm{Abs}\left[\frac{P_i - O_i)}{O_i}\right] \times 100 \tag{4}$$

$$d = 1.0 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \tag{5}$$

where P_i is the ith simulated value, O_i is the ith observed value, $\bar{O}$ is the mean observed value, and n is the number of data pairs.

3. Results and discussion

At Sidney, precipitation during the April to August period (Table 10) was 89% of normal (28.6 cm, 1971–2000) in 2004 and 133% of normal in 2005. At Akron, precipitation was 77% of normal (30.2 cm, 1971–2000) in 2004 and 98% of normal in 2005 for the same period. Despite some month-to-month variation, average daily temperatures for the April to August growing seasons in 2004 and 2005 were near normal (between 6.7 and 24.1 °C) at both locations (data not shown).

3.1. Triticale

3.1.1. Calibration

Calibrations of model parameters for accurate soil water simulations are critical for correct quantification of soil water stress that controls crop growth and development. At both Akron and Sidney, soil water measurements were available at approximately bi-weekly intervals for comparison with the model simulations. In the High water treatment in 2004 at Akron (calibration data set), 16.8 cm of PAW was available in the 120 cm soil profile at planting (Table 1) which served as the initial soil water content for the calibration of the model. Simulated volumetric soil water in the different layers during the 2004 triticale growing season corresponded well with measured values (RMSE = 0.027 $m^3 m^{-3}$). Total water in the 120 cm soil profile was also modeled well (RMSE = 0.7 cm, MRE = 3%, d = 0.98) (Table 11, Fig. 1). We considered these calibration results to be adequate since RZWQM2–DSSAT v4.0 is a one dimensional model in which a single soil profile (point measurement) represents the average conditions in a heterogeneous field that is spatially variable in soil water content.

Triticale was harvested for forage on 23 June (immediately after anthesis), and as such the crop did not complete all the phenological stages and reach physiological maturity (Table 2). The simulated emergence date had an error of 1 day, and the

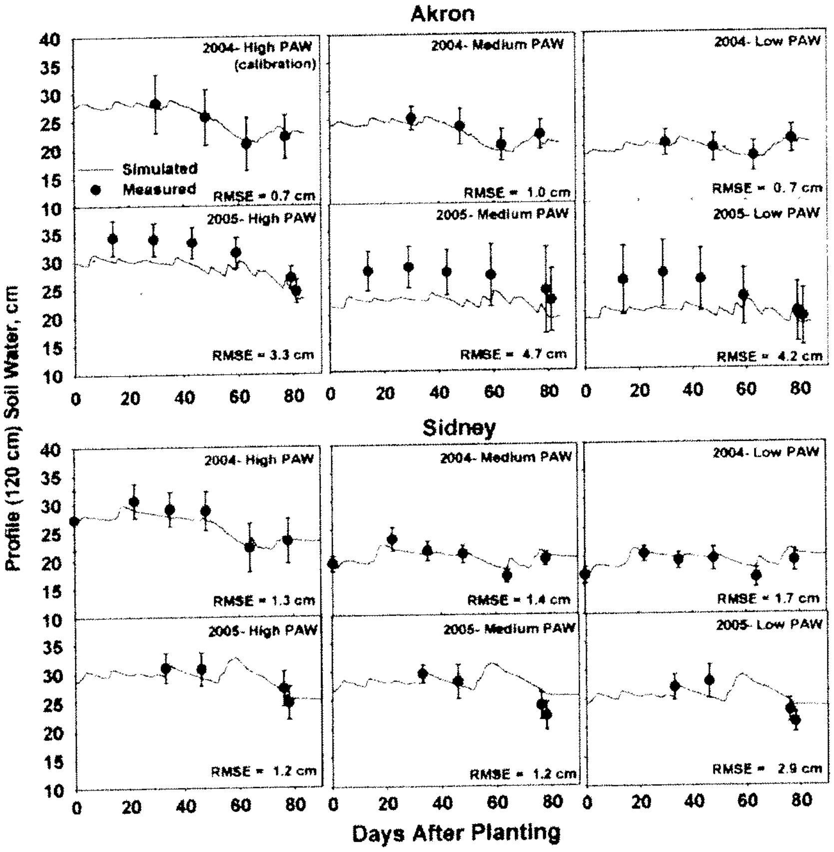

Fig. 1. Measured and simulated soil water (120 cm profile) for spring triticale at Akron, CO and Sidney, NE in response to High, Medium, and Low plant available water (PAW) in the soil at planting in 2004 and 2005. Error bars represent one standard deviation of the mean.

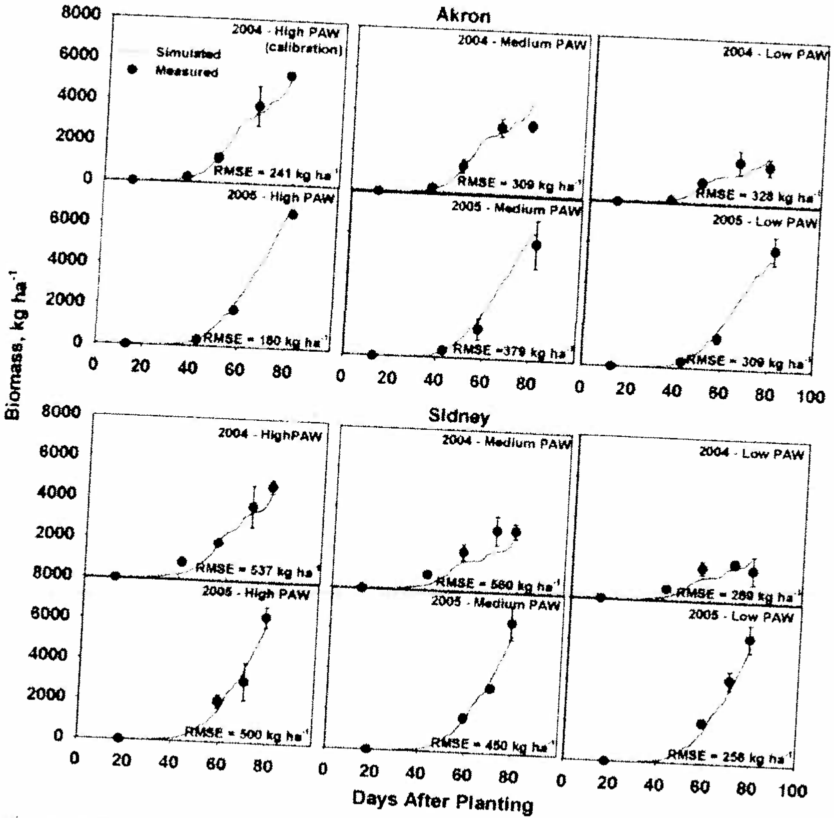

Fig. 3. Measured and simulated spring triticale biomass at Akron, CO and Sidney, NE in response to High, Medium, and Low plant available water (PAW) in the soil at planting in 2004 and 2005. Error bars represent one standard deviation of the mean.

Table 12

Root Mean Square Error (RMSE), Mean Relative Error (MRE), and Willmott's index of agreement (*d*) for simulations of soil water, LAI, grain yield, and biomass of proso millet in 2004 and 2005 at Akron, CO and Sidney, NE in response to High, Medium, and Low plant available water (PAW) in the soil at planting and from proso millet grown in the alternative crop rotation (ACR) experiments at Akron from 2003 to 2006.

Variables	High PAW			Medium PAW			Low PAW		
	RMSE	MRE, %	*d*	RMSE	MRE, %	*d*	RMSE	MRE, %	*d*
Akron 2004									
Soil water, $m^3 m^{-3}$	0.039	–	–	0.036	–	–	0.038	–	–
Soil profile water, cm	1.9	6	0.92	2.5	7	0.75	2.0	7	0.62
LAI, $m^2 m^{-2}$	0.97	33	0.78	1.0	35	0.72	0.97	39	0.65
Grain yield, kg ha^{-1}	28	2	–	272	23	–	565	87	–
Biomass, kg ha^{-1}	588	30	0.98	955	29	0.9s5	712	32	0.96
Sidney 2005									
Soil water, $m^3 m^{-3}$	0.033[a]	–	–	–	–	–	0.027	–	–
Soil profile water, cm	2.2[a]	8[a]	0.97[a]	2.3	8	0.97	1.2	5	0.99
LAI, $m^2 m^{-2}$	0.83[a]	21[a]	0.92[a]	0.86	36	0.92	0.90	38	0.91
Grain yield, kg ha^{-1}	428[a]	10[a]	–	549	12	–	459	10	–
Biomass, kg ha^{-1}	411[a]	6[a]	1.00[a]	791	10	0.99	1106	15	0.99
	ACR Akron 2003			ACR Akron 2004			ACR Akron 2005		
Soil water, $m^3 m^{-3}$	0.068	–	–	0.058	–	–	0.070	–	–
Soil profile water, cm	2.2	6	0.96	2.3	10	0.91	6.7	21	0.38
LAI, $m^2 m^{-2}$	0.41	21	0.93	–	–	–	0.89	40	0.80
Grain yield, kg ha^{-1}	153	6	–	71	3	–	352	37	–
Biomass, kg ha^{-1}	1603	80	0.85	1549	20	0.95	1030	19	0.94
	ACR Akron 2006								
Soil water, $m^3 m^{-3}$	0.041	–	–						
Soil profile water, cm	2.2	9	0.95						
LAI, $m^2 m^{-2}$	0.64	19	0.88						
Grain yield, kg ha^{-1}	188	12	–						
Biomass, kg ha^{-1}	868	22	0.97						

[a] Calibration results.

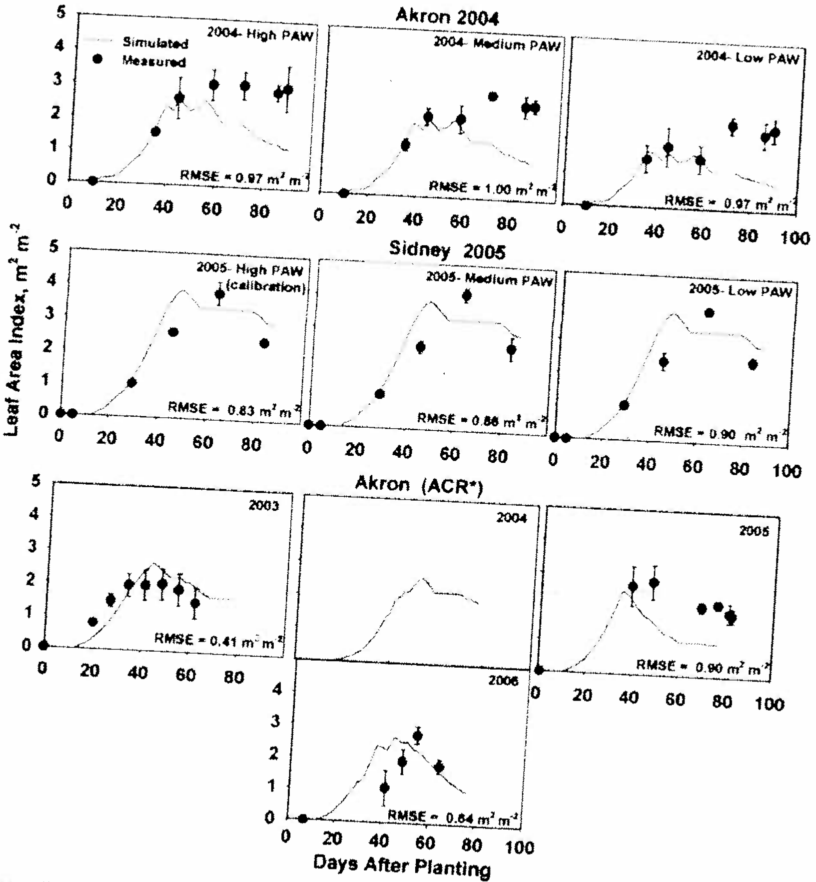

Fig. 5. Measured and simulated proso millet leaf area index at Akron, CO and Sidney, NE in response to High, Medium, and Low plant available water (PAW) in the soil at planting in 2004 and 2005, and in the alternative crop rotation (ACR) experiment at Akron during 2003–2006. Error bars represent one standard deviation of the mean.

with an MRE of 10% (simulated value was 428 kg ha^{-1} lower than the measured value). The model only simulated a few developmental stages (emergence, anthesis, physiological maturity) such that only crop emergence date was available for comparison of simulated crop phenological development with measured data. The simulated emergence date was 2 days later than the measured emergence date (Table 3).

3.2.2. *Validation*

Soil water amounts and changes with proso millet growth were reasonably simulated across treatments, years, and locations (Fig. 4). Crop biomass, LAI, and grain yield of proso millet increased with initial PAW at Akron in 2004 (Figs. 5–7). The difference in available soil water between High and Low PAW treatments at millet planting in 2004 at Akron was 100 mm. Felter et al. (2006) reported that 58% of the variability in proso millet grain yield in the experiment was explained by initial PAW. Crop emergence was correctly simulated as 10 days after planting (Table 3). However, simulated anthesis date was 7 days later than observed and simulated physiological maturity was 4 days later than observed. These errors in rate of development did not affect the overall simulations of the crop drastically. Soil water was adequately simulated in 2004 with RMSEs between 0.036 and 0.039 m^3 m^{-3} for the volumetric soil water in different soil layers. Water in the 120 cm soil profile was simulated with RMSEs between 1.9 cm (MRE = 6% and $d = 0.92$) and 2.5 cm (MRE = 7% and $d = 0.75$) (Table 12 and Fig. 4). Leaf area index in 2004 was simulated less accurately with RMSEs of 0.97 m^2 m^{-2} (MRE = 33% and $d = 0.78$), 1.0 m^2 m^{-2} (MRE = 35% and $d = 0.72$) and 0.97 m^2 m^{-2} (MRE = 39% and $d = 0.65$) in the High, Medium and Low PAW treatments, respectively (Table 12 and Fig. 5). However, biomass gain with crop development was reasonably well simulated with RMSEs between 588 kg ha^{-1} (MRE = 30% and $d = 0.98$) in the High PAW treatment and 955 kg ha^{-1} (MRE = 29% and $d = 0.95$) in the Medium PAW treatment (Table 12 and Fig. 6). Grain yield simulations across the three PAW treatments in 2004 had an RMSE of 196 kg ha^{-1} and MRE of 37%. While the grain yields simulated in the High and Medium PAW treatments were simulated with MREs of 2% and 23%, the grain yield in the Low PAW treatment showed an MRE of 87%. The lower accuracy in grain yield simulations for the Low water treatment in 2004 occurred due to the model's low responsiveness regarding biomass partitioning changes to grain in response to water stress (inaccurately simulating changes to harvest index (HI) that occur in response to water stress). Measured HI for the High, Medium, and Low PAW treatments were 0.23, 0.18 and 0.11, respectively. However, simulated HI for all three treatments remained at 0.24. Further studies are needed to correctly quantify HI changes in response to water stress.

At Sidney in 2005, measured grain yield was not significantly affected by soil water at planting ($P = 0.90$) (Fig. 7), with all treatments yielding about 4000 kg ha^{-1}. Little difference existed in water availability between treatments in 2005 (Table 1). Also, measured maximum LAI (Fig. 5) and biomass (Fig. 6) in 2005 did not show any significant difference between the High, Medium,

Table 13
Root Mean Square Error (RMSE), Mean Relative Error (MRE), and Willmott's index of agreement (*d*) for simulations of soil water, LAI, and biomass of foxtail millet in 2004 and 2005 at Akron, CO and Sidney, NE in response to High, Medium, and Low plant available water (PAW) in the soil at planting.

Variables	High PAW			Medium PAW			Low PAW		
	RMSE	MRE, %	*d*	RMSE	MRE, %	*d*	RMSE	MRE, %	*d*
Akron 2004									
Soil water, $m^3 m^{-3}$	0.030^a	–	–	0.032	–	–	0.023	–	–
Soil profile water, cm	1.5^a	5^a	0.92^a	2.9	9	0.73	1.5	5	0.81
LAI, $m^2 m^{-2}$	0.79^a	20^a	0.95^a	0.68	24	0.95	0.57	27	0.93
Biomass, kg ha^{-1}	194^a	10^a	1.00^a	444	21	0.98	709	20	0.95
Sidney 2005									
Soil water, $m^3 m^{-3}$	0.025	–	–	0.028	–	–	0.021	–	–
Soil profile water, cm	1.3	4	0.98	1.2	3	0.98	0.3	1	1.00
LAI, $m^2 m^{-2}$	0.86	34	0.96	0.87	29	0.97	1.0	48	0.95
Biomass, kg ha^{-1}	336	22	1.00	298	27	1.00	201	9	1.00

^{a} Calibration results.

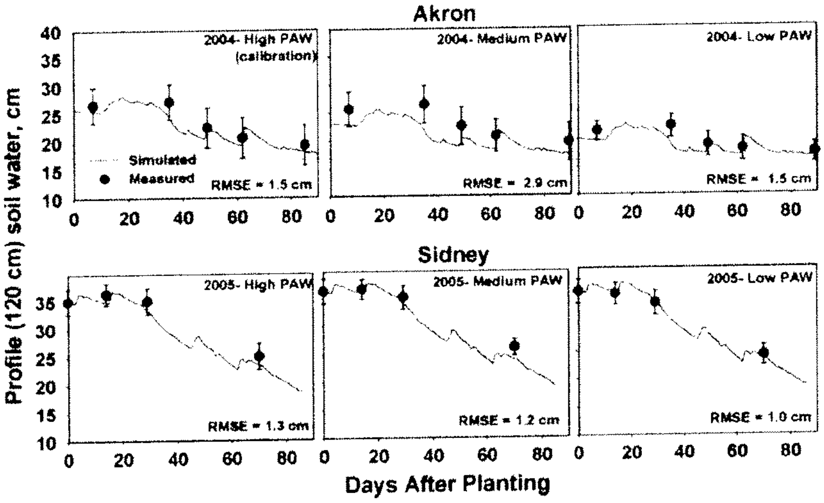

Fig. 8. Measured and simulated soil water (120 cm profile) for foxtail millet at Akron, CO and Sidney, NE in response to High, Medium, and Low plant available water (PAW) in the soil at planting in 2004 and 2005. Error bars represent one standard deviation of the mean.

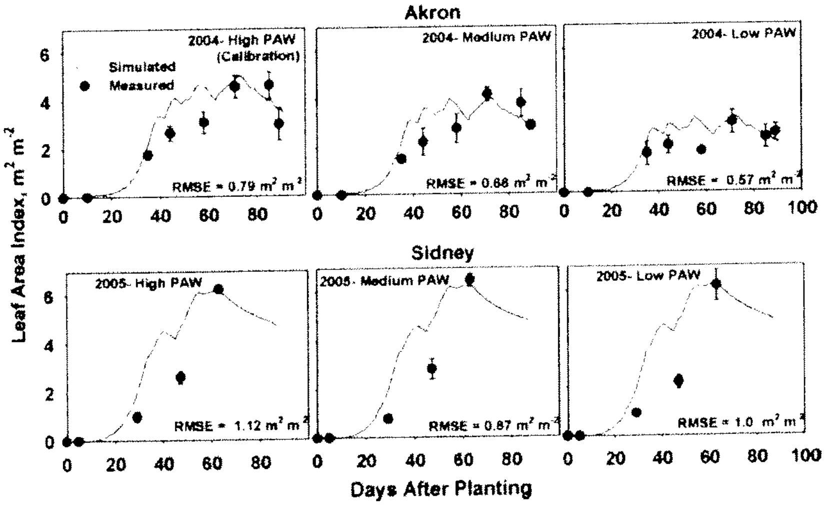

Fig. 9. Measured and simulated foxtail millet leaf area index at Akron, CO and Sidney, NE in response to High, Medium, and Low plant available water (PAW) in the soil at planting in 2004 and 2005. Error bars represent one standard deviation of the mean.

development to soil water at planting across different PAW treatments. Simulated crop emergence occurred 7 days after planting compared with observed emergence 5 days after planting (Table 3). Soil water was accurately simulated at Sidney in 2005 leading to reasonably accurate simulations of maximum LAI and biomass development in the three PAW treatments (Figs. 8, 9 and 10). Soil water in different soil layers was simulated with an RMSE between 0.021 and $0.028\,\mathrm{m^3\,m^{-3}}$ for the three treatments (Table 13). Total PAW in the soil profile was simulated with an RMSE of 1.3 cm or less and an MRE of 4% or less in the three treatments. RMSEs of LAI simulations ranged between $1.0\,\mathrm{m^2\,m^{-2}}$ ($\mathrm{MRE} = 48\%$ and $d = 0.95$) and $0.86\,\mathrm{m^2\,m^{-2}}$ ($\mathrm{MRE} = 34\%$ and $d = 0.96$) (Table 13). Mid-season LAI was over-predicted by the model. Simulations of the time progression of biomass matched well with the measurements resulting in RMSEs below $336\,\mathrm{kg\,ha^{-1}}$ and MREs below 27% across the three treatments (Table 13 and Fig. 10). In general, validation of the model simulations with limited data (one year each at two locations) showed that foxtail millet and its responses to different initial PAW could be satisfactorily predicted with the model developed.

4. Summary and conclusions

Wheat farmers in the Great Plains could benefit greatly from the availability of a short-season crop that could be produced during the spring or summer months prior to planting the next wheat crop in late September or early October. Experiments with triticale and foxtail millet as forage crops and proso millet as a grain/forage crop showed the potential of these short-season crops for use in a flexible summer fallow cropping system, and the amount of plant available water in the soil at planting may be a significant indicator of subsequent yield (Felter et al., 2006). However, these relationships can vary between seasons and locations depending on the amount and distribution of growing season precipitation and other weather variables experienced subsequent to planting. The models developed for simulation of these three crops are potential tools that can integrate and synthesize information from such short-season experiments and effectively extend the results to other seasons, soils, and climates (e.g., for selection of the crop best suited in a particular season at a particular location). For simulation of these crops, the DSSAT v4.0 crop simulation modules as available in RZWQM2-DSSAT v4.0 were successfully adapted and calibrated using the crop growth and development data collected from experiments at Sidney, NE and Akron, CO. The CSM–CERES-Wheat v4.0 module was adapted for simulation of spring triticale, and the CSM-CERES-Sorghum module was adapted for simulation of both proso millet and foxtail millet. Specifically, the species and ecotype parameters for the crops in the CSM modules were adapted for simulation of the crops. Each crop module was further calibrated for cultivar traits (genetic coefficients) for simulating the specific crop cultivars used in the experiments. The three crop modules developed for spring triticale, proso millet, and foxtail millet all simulated crop growth and development well and also adequately responded to different levels of PAW in the soil at planting in different years (2004 and 2005) and at different locations (Sidney and Akron). Because spring triticale and foxtail millet were harvested for forage before reaching physiological maturity, the models developed for these two crops could not be tested for simulation of grain yield. Further experiments are required to grow these crops to full maturity, and measure the grain yields for calibration and validation of the model simulations. The crop modules developed in this study have shown adequate potential for future simulations of these crops in rotations with other crops in northeastern Colorado and western Nebraska. Further testing should be done to validate these models for different soil types and climates (locations) so that these models can be used for decision support relating to crop management throughout the High Plains. Developing decision support for selection of the best suited short-season summer crop in a crop rotation in a particular season at a location based on measured initial PAW in the soil by using RZWQM2–DSSATv4.0 and historical climate records would be a challenging example of the application of the model in strategic farm management, and will be taken up and reported in subsequent studies.

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