

A Wheat Grazing Model for Simulating Grain and Beef Production: Part II-Model Validation

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ABSTRACT

Computer models must be thoroughly evaluated before being used for decision-making. The objective of this paper is to evaluate the ability of a newly developed wheat grazing model to predict fall-winter forage and winter wheat (*Triticum aestivum* L.) grain yield as well as daily weight gains of steer (*Bos taurus*) grazing on wheat pasture in Oklahoma. Experimental data of three independent field studies were used. The first was a variety trial in which fall-winter forage and grain yields were harvested. The second was a planting date experiment in which forage in the fall-winter period and grain yields were harvested. The third was a steer grazing experiment in which standing wheat biomass and steer weight gain were monitored. For the variety trials, the model efficiency (ME), which reflects how well model predictions match measured data (1 means a perfect match), was 0.102 for fall-winter forage prediction and 0.367 for grain yield. For the planting date experiment, the ME was 0.615 for predicting fall-winter forage yields and 0.409 for grain yields when a root downward extension rate of 20 mm d⁻¹ was used. In the steer grazing experiment, the relationship between average daily weight gain and forage allowance was adequately represented by the model. For the total steer weight gains in a wide range of stocking rates and grazing durations, the ME was 0.616. Overall results show that the model, if well calibrated, has the potential to predict fall-winter forage and grain yields as well as mean daily weight gain per steer.

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Abbreviations:

BW:	body weight
DM:	dry matter
ME:	model efficiency
MPAE:	mean percentage absolute error
MPE:	mean percentage error
RMSE:	root mean square error

INTRODUCTION

Winter wheat is commonly grown in the Southern Great Plains and is often managed as a dual-purpose crop for grain and cattle production. Millions of hectares of winter wheat in the region are grazed between late fall and early spring annually for added revenues. Redmon et al. (1995) reported that the averaged annual net returns to the wheat grain-cattle enterprise in Oklahoma from 1984 to 1993 was about 155 US\$ ha⁻¹, among which cattle production contributed about 41%. Although grazing on winter wheat is economically desirable, management of dual-purpose wheat production is complex because of the multifaceted interactions and tradeoffs between cattle and wheat grain production, which are further complicated by the effect of variable weather in the region (Rodríguez et al., 1990; Hossain et al., 2003). Several studies showed that light to moderate grazing of winter wheat before first hollow stem had little effect on wheat grain yield, but grazing past first hollow stem reduced grain yield considerably (Winter and Thompson, 1987; Christiansen et al., 1989; Redmon et al., 1996; Fieser et al., 2004).

Biophysically based wheat grazing models have the potential of optimizing management decisions and developing alternative management options to maximize economic returns to the wheat grain-cattle production enterprise. Wheat grain yield is generally decreased with increased grazing intensity and duration, especially beyond the first hollow stem or the Zadok's stage of 3.0 (Zadoks et al., 1974). However, beef production per hectare as a product of grazing duration, daily weight gain, and stocking rates is often increased with increased grazing intensity and duration (Phillips and Albers, 1999). The economic tradeoff relationship provides a unique opportunity of using a corroborated wheat grazing model to optimize management options and decisions on, for example, when to terminate wheat grazing.

A wheat grazing model composed of wheat growth, cattle growth, and wheat-cattle interaction was developed to simulate production of wheat grain and stocker steer grazing on winter wheat from late fall to early spring (Zhang et al., 2008). The wheat growth is simulated by the wheat module in the Decision Support Systems for Agrotechnology Transfer (DSSAT) model (v4.02) (Jones et al., 2003), and the cattle growth is based on a metabolizable energy balance. For the wheat-cattle interface, individual leaf areas, as well as leaf, stem, and reserve weights and their corresponding N contents are adjusted for grazing on a daily basis. The model

simulates wheat growth and cattle growth interactively and dynamically, and thus is capable of simulating the tradeoffs between beef and grain production and rendering a unique opportunity to optimize wheat grain-beef production systems. However, the model has not been corroborated with field measured data.

Model calibration and evaluation are essential before it can be successfully used for decision-making. The objective of this study was to evaluate the model's ability to predict wheat growth, re-growth as well as grain and beef production using clipping and grazing data collected at Oklahoma State University (OSU) experiment stations.

MATERIALS AND METHODS

The wheat grazing model was evaluated using experimental data from three independent field experiments conducted at three locations in Oklahoma. The data set included the OSU variety trials at Chickasha (35°1'56" N, 97°54'52" W) and Marshall (36°7'7" N, 97°36'5" W), OK (OSU-CES, 1990-2005), the planting date field trials at Lahoma (36°23'4" N, 98°6'41" W), OK (Hossain et al., 2003), and the dual-purpose winter wheat and steer grazing experiments at Marshall (Kaitibie et al., 2003).

Experimental Data of Variety Trials

The goal of the variety trials was to facilitate wheat variety selection for fall forage production in Oklahoma under the conditions in which fertility was not yield-limiting (OSU-CES, 1990-2005). The TAM 101 and Jagger varieties were selected for this study because we had calibrated the two varieties using three-years of field experiment data collected at El Reno (35°32'54" N, 98°2'11" W), OK. Both varieties are semidwarf and early maturing. Detailed crop management information such as planting dates, and forage clipping dates and heights can be found in Table 1 for the Chickasha site in south-central Oklahoma and in **Table 2** for the Marshall site in north-central Oklahoma. The TAM 101 variety was planted before 1993 while Jagger was planted after 1994 at both sites. Wheat forage was harvested approximately 50-64 mm above the ground surface using a sickle bar forage harvester before 1996 at both sites (OSU-CES, 1990-2005). Following 1997, wheat forage was clipped by hand to the soil surface using meter row samples, and the remainder of the plot area was mowed at approximately 60-mm height after each clipping. The re-growth was measured by subsequently clipping meter row samples to the soil surface at the same location.

Table 1. Experimental data of the variety trials of dual-purpose and grain-only hard red winter wheat at Chickasha, OK.

Year	Variety	Planting date	Clipping height mm	First clipping		Re-growth		Grain yield	
				Date	Forage yield kg ha ⁻¹	Clipping date	Forage yield kg ha ⁻¹	Dual-purpose	Grain-only
1990-1991	TAM 101	9/24†	60	11/16	1811	12/7	911	3029	
1991-1992	TAM 101	10/1†	60	2/14	1879				
1994-1995	Jagger	9/19†	60	11/3	744	12/19,2/24	3134	1247	
1995-1996	Jagger	9/14†	60	11/17	2333	12/12,3/5	1111	1389	
1996-1997	Jagger	9/9†	60	11/15	2041	12/16	517	1007	
1997-1998	Jagger	9/22†	S§	12/15	3225			2648	4689
1998-1999	Jagger	9/25†,10/20†	S	12/14	3225			2187	2449
1999-2000	Jagger	9/9†,11/9†	S	10/26	1333	12/7	1097	2187	3858
2000-2001	Jagger	9/19†,10/19†	S	12/6	2396			3559	4058
2001-2002	Jagger	9/13†,10/18†	S	11/5	1963	12/6	657	2362	2721
2002-2003	Jagger	9/25†	S	12/2	2486			2052	

† dual-purpose; ‡ grain-only; § S=clipped to the surface for forage and mowed rest of plots at 60 mm height

Dual-purpose and grain-only wheat experiments were conducted from 1997 to 2002 at Chickasha and from 1997 to 2005 at Marshall. Those data provided useful information on evaluating the effects of cattle grazing or mechanical clipping on grain yield. At Chickasha, wheat was mechanically clipped one or two times in late fall to simulate grazing. At Marshall, the plots were actually grazed by stocker steers in late fall and winter. However, the grazing durations and stocking rates, normally ranged from 1 to 2 head ha⁻¹, were unknown except for 2002-2004 crop years. An average stocking rate of 1.5 head ha⁻¹ with an average of 250 kg body weight was assumed in evaluation. A common grazing period from 15 November to 15 February of the following year was also assumed for years with missing records. But for 2000-2001, a grazing period from 15 February to 15 March was used because simulated forage was insufficient for grazing until 15 February due to late planting (**Table 2**).

In the variety trials, the limitation of soil fertility on forage and grain production was largely eliminated by fertilization following soil test recommendations. In general, total plant available N of 112 kg ha⁻¹ was recommended for grain-only and 212 kg ha⁻¹ for dual-purpose wheat [the common recommendations were 2.24 kg ha⁻¹ (2 lb acre⁻¹) N for 67 kg ha⁻¹ (1 bu acre⁻¹) grain and 34 kg ha⁻¹ (30 lb acre⁻¹) N for 1120 kg ha⁻¹ (1000 lb acre⁻¹) forage, and the target yields normally used in Oklahoma were 3360 kg ha⁻¹ (50 bu acre⁻¹) grain and 3360 kg ha⁻¹ (3000 lb acre⁻¹) wheat forage] (Hossain et al., 2004). Since most fertilization dates were unavailable, 92- and 192-kg N ha⁻¹ were applied at planting each year for grain-only and dual-purpose wheat, respectively (note that 20-kg ha⁻¹ soil residual N was assumed at the beginning of simulation). If measured forage or grain yield was above the target yield, N application rates were scaled up based on the recommendation rates given above, because winter N application rates, for example, were based on harvested fall forage yields. Note that the fertilization rates used in the simulation should be close to the actual application rates because they were calculated based on the recommendation rates as was used in the experiments, but the application time was assumed to be at planting.

Based on the measured data combined with the regional common management practices, a seeding rate of 67 kg ha⁻¹ for grain-only and 134 kg ha⁻¹ for dual-purpose wheat was used in compiling the DSSAT input files. Conventional tillage systems were used throughout the trials but the actual tillage methods and dates were unavailable. A generic tillage system common to

Table 2. Experimental data of the variety trials of dual-purpose and grain-only hard red winter wheat at Marshall, OK (date in mo/d).

Year	Variety	Planting date	Fall forage			Winter forage			Grain yield	
			Clipping height mm	Clipping date	Forage yield kg ha ⁻¹	Clipping date	Forage yield kg ha ⁻¹	Dual- purpose	Grain-only	
1989-1990	TAM 101	9/18†	60	11/16,12/20	732	3/5	625	1130	----- kg ha ⁻¹ -----	
1990-1991	TAM 101	9/12†	60	11/6,12/5	1389	3/5	134	771		
1991-1992	TAM 101	9/27†	60	12/25‡	1201			1929		
1992-1993	TAM 101	9/10-15†	60	12/15‡	1341	2/15‡	725	1600		
1993-1994	TAM 101	9/10†‡	60	10/22	640	3/1	477	1027		
1994-1995	Jagger	9/12†	60	10/26,12/7	2180					
1996-1997	Jagger	9/3†	60	12/15	818	3/1	1296	1020		
1997-1998	Jagger	9/3†,10/7§		grazing duration assumed	11/15-2/15¶			3850	4653	
1999-2000	Jagger	9/22†,11/6§		grazing duration assumed	11/15-2/15¶			2514	2449	
2000-2001	Jagger	10/10†§		grazing duration assumed	2/15-3/15¶			3244	3905	
2001-2002	Jagger	9/10†,10/2§		grazing duration assumed	11/15-2/15¶			1956	2608	
2002-2003	Jagger	9/25†,10/15§		grazing duration measured	11/10-3/7¶			3610	3402	
2003-2004	Jagger	9/7†,10/10§		grazing duration measured	11/11-3/7¶			2826	3552	
2004-2005	Jagger	8/31†,10/29§		grazing duration assumed	11/15-2/15¶			739	1875	

† dual-purpose; ‡ assumed date; § grain-only; ¶ assumed stocking rate was 1.5 head ha⁻¹ and body weight was 250 kg.

Table 3. Planting dates (mo/d) of winter wheat and number of varieties in the planting date trials at Lahoma, Oklahoma.

Variable	1991- 1992	1992- 1993	1993- 1994	1994- 1995	1995- 1996	1996- 1997	1997- 1998	1998- 1999	1999- 2000
Planting date 1	8/28	9/04	8/27	8/24	9/11	8/30	8/28	9/15	9/10
Planting date 2	9/09	9/18	9/10	9/7	9/29	9/13	9/11	9/29	9/23
Planting date 3	9/27	10/1	9/24	9/21	10/13	10/2	9/29	10/13	10/7
Planting date 4	10/7	10/15	10/7	10/5	10/27	10/11	10/10	10/27	10/21
Planting date 5						10/31	10/22	11/16	11/4
No. of varieties	1	1	1	6	4	8	6	12	6

the region including an offset disk operation on 25 June, a chisel on 25 July, and a field cultivation on 25 August as well as at planting was used for each year. For simplicity, each year was simulated independently starting on 20 June, and a 5% of plant available water by volume and residual 20 kg N ha⁻¹ were set as initial values at the start. These tillage operations and initial conditions were also used in the following two experiments.

Experimental Data of Planting Date Study

For the planting date field trials at Lahoma in north-central Oklahoma, the objective was to determine the response of wheat fall-winter forage and grain yields to planting date (Hossain et al., 2003). The datasets were useful for evaluating the effect of forage harvesting and planting date on grain yield. The experiment ran from 1991 to 2000, and planting dates varied from late August to mid-November (Table 3). Each planting date treatment was replicated four times, and the test plots were randomized in a complete block design. In the first three crop years or growing seasons, the Karl variety was seeded on all plots at several seeding rates. Beginning the 1994-1995 crop year, a constant seeding rate of 134 kg ha⁻¹ was used across all plots, and more varieties were included (Table 3). Although no detailed records on the varieties grown each year could be found, we are sure that the 2180, 2163, and Jagger varieties were included in some years and that all varieties were semidwarf and early maturity.

To simulate grazing, the plots were mechanically clipped about 80 mm above the soil surface using a sickle bar forage harvester (personal communication with Richard Austin²). The first clipping was made in late fall, and the second in late winter before first hollow stem. The total forage yield was the sum of the two clippings. The central 5.3-m strip on each plot was harvested for grain yield with a small plot combine. All plots were sufficiently fertilized to have plant available N of 212 kg ha⁻¹ as recommended for dual-purpose wheat discussed above so that soil fertility was not the yield-limiting factor (Krenzer et al., 2000; Hossain et al., 2003).

For compiling model input files, certain management operations like tillage operations, fertilization and clipping dates had to be generalized across all years because many of them were unavailable. The 192-kg ha⁻¹ N was incorporated into 0.1-m top soil layer at planting. If measured forage or grain yield was above the target values, N fertilizer rates were scaled up accordingly. The first clipping was assumed on 15 December, and the second on 1 March. The Jagger variety that is representative of a semidwarf and early maturity type was used in all simulations.

Experimental Data of Dual-purpose Wheat and Steer Grazing

The dual-purpose winter wheat and steer grazing experiment was conducted at the Wheat Pasture Research Unit (WPRU) of OSU at Marshall. The experimental data from 1989 to 2000 were used in this study (Horn et al., 1995; Redmon et al., 1996; Kaitibie et al., 2003). In a typical year, an offset disk operation was performed in June after wheat harvest, followed by a chisel operation in July, a pass with a field cultivator in August and another in September (Kaitibie et al., 2003). Detailed management information including planting date, varieties, stocking rates, grazing dates and duration, and stocker steer data is summarized in Table 4. Only semidwarf and early maturity varieties were included in this study (**Table 4**). Wheat was normally seeded in the first week of September at a rate of 134 kg ha⁻¹. Wheat grazing normally started in early November and continued until the development of first hollow stem, which varied from late February to early March. Standing wheat forage biomass (canopy top weight) was clipped by hand to the ground level three or four times during a growing season immediately before and during grazing, normally one clipping in each calendar month. Wheat grain for each stocking rate treatment was combine harvested in June. Total plant available N of 212 kg N ha⁻¹

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Table 4. Wheat variety, stocking rate, grazing duration, average daily weight gain, average standing wheat forage during grazing, and grain yield of the dual-purpose wheat and grazing experiments at Marshall, OK (date in mo/d)†.

Year (planting date)	Variety	Stocking rate‡ head ha ⁻¹	Grazing duration		Initial steer weight kg head ⁻¹	Average daily weight gain kg head ⁻¹ d ⁻¹	Average forage during grazing kg ha ⁻¹	Grain yield Kg ha ⁻¹
			Start	End				
1989-1990 (9/10)	2157	1.24	11/17/1989	03/12/1990	209.7	0.967	1975	
1990-1991(9/16)	2157	1.24	11/21/1990	03/08/1991	212.9	0.908	1583	
		1.51	“	“	213.8	0.940	1420	
		1.78	“	“	213.8	0.799	1073	
1991-1992 (9/29)	2157	1.26	12/05/1991	02/28/1992	242.9	0.990	1720	
1992-1993 (9/7)	Karl	1.24	11/18/1992	03/10/1993	217.9	0.817	1003	2160
		1.51	“	“	218.8	0.745	676	1218
		1.78	“	“	214.7	0.436	638	1662
		2.05	“	“	220.2	0.499	626	1029
	2163	1.24	“	“	219.7	0.999	1541	2005
		1.51	“	“	220.2	0.872	976	2348
		1.78	“	“	222.5	0.631	837	1204
		2.05	“	“	217.0	0.227	702	1198
	2180	1.24	“	“	222.0	0.990	1035	1803
		1.51	“	“	218.8	0.863	1011	1877
		1.78	“	“	220.6	0.658	621	1783
		2.05	“	“	221.1	0.431	576	1285
	7853	1.24	“	“	217.9	0.767	924	1702
		1.51	“	“	211.1	0.518	722	1938
		1.78	“	“	218.4	0.309	567	1225
		2.05	“	“	217.0	0.449	608	1352
1993-1994 (9/8)	Karl	1.04	11/02/1993	03/15/1994	225.6	1.053	2688	1924
		1.51	“	“	226.5	1.035	1841	1998
		1.78	“	“	228.4	1.108	1757	1722
		2.05	“	“	222.9	1.017	1633	1709
	2163	1.04	“	“	232.0	1.085	2213	2005
		1.51	“	“	226.1	1.081	2443	2173
		1.78	“	“	232.4	1.108	2087	1393
		2.05	“	“	228.8	1.094	1879	1608
	2180	1.04	“	“	222.0	1.171	2107	2019
		1.51	“	“	225.6	1.112	2098	1709
		1.78	“	“	229.7	1.044	1717	1413
		2.05	“	“	227.0	0.917	1262	1325
	7853	1.04	“	“	231.1	1.099	2479	1729
		1.51	“	“	221.1	1.053	1572	1426
		1.78	“	“	232.0	1.035	1673	1642
		2.05	“	“	227.0	0.972	1477	1393
1994-1995 (9/14)	2180	0.96	11/01/1994	02/25/1995	248.3	1.085	3170	1467
		1.41	“	“	254.2	1.326	3241	1211
		1.88	“	“	247.4	1.158	2634	1285
		2.25	“	“	252.4	1.044	1461	1339
	7853	0.89	11/01/1994	03/06/1995	251.5	1.149	2248	1043
		1.09	“	“	239.3	1.103	2209	1413
		1.61	“	“	246.5	1.153	1747	1312

		2.30	“	“	252.4	0.885	1285	1460
1996-1997 (9/3)	2180	1.14	10/25/1996	02/24/1997	212.0	1.026	2820	680
		1.09	“	“	213.4	1.090	2088	902
		1.73	“	“	212.5	0.999	2278	1312
		2.69	“	“	211.1	0.922	2076	922
	7853	0.94	10/25/1996	03/08/1997	210.7	1.062	2252	3001
		1.04	“	“	212.0	0.953	1950	2543
		1.61	“	“	212.9	1.008	2088	2187
		2.25	“	“	212.5	0.790	1787	2375
1997-1998 (9/3)	Tonkawa	0.84	10/25/1997	02/20/1998	269.7	1.298	2904	2994
		1.04	“	“	253.3	1.303	2480	2954
		1.38	“	“	246.5	1.126	1828	2913
		2.05	“	“	215.2	1.076	1714	3183
1998-1999 (9/28)	Tonkawa	0.94	11/12/1998	03/02/1999	261.1	1.012	1746	2166
		1.16	“	“	256.1	1.312	1291	2922
		1.53	“	“	263.8	1.026	1249	2685
		2.20	“	“	262.0	0.990	2247	2352
1999-2000 (9/18)	Tonkawa	1.04	11/30/1999	02/28/2000	234.3	1.394	1238	2835
		1.38	“	“	234.3	1.180	835	2705
		1.56	“	“	237.9	1.303	475	1754
		1.38	“	“	239.3	1.339	1104	3044
		2.62	“	“	229.3	0.708	574	2702
		2.87	“	“	229.7	0.690	820	2094

† After Kaitibie et al. (2003); ‡ Average stocking rates over the grazing season.

was recommended for the dual-purpose wheat as discussed above to avoid nutrient deficiency. Typically, based on soil test N, a predetermined amount of anhydrous ammonia (82-0-0) was injected in August and about 60-kg ha⁻¹ diammonium phosphate (18-46-0) was placed in furrows at planting each year (Kaitibie et al., 2003).

Steers were vaccinated and fed with bermudagrass hay and a soybean meal-based supplement before placement on wheat pasture. The body weight at the initiation of grazing mostly ranged from 210 to 250 kg per head (Table 4). The steers were provided free access to a high calcium commercial mineral mixture, and received no other supplemental feed except for limited amounts of alfalfa hay when snow cover limited access to wheat forage (Kaitibie et al., 2003). Stocking rates varied from about 1 to 2.9 head ha⁻¹. Stocking rates remained constant each year for the first five grazing seasons, and were adjusted based on forage availability at placement as well as during grazing so that forage allowance per steer (or grazing pressure) stayed constant throughout the grazing season in each stocking rate treatment.

For model runs, 170-kg ha⁻¹ N was applied on August 20, and 25-kg ha⁻¹ N was banded in furrows at planting each year. Since crop coefficients of the varieties were unavailable, the Jagger variety was used to represent the semidwarf and early maturity group.

Table 5. Calibrated variety coefficients of two hard red winter wheat varieties at El Reno, Oklahoma†.

Variety	P1V	P1D	P5	G1	G2	G3	PHINT
TAM 101	40	70	450	12	30	1.5	90
Jagger	40	63	450	17	25	1.5	90

†P1V: days at optimum vernalizing temperature required to complete vernalization; P1D: percentage reduction in development rate in a photoperiod 10 h shorter than the optimum relative to that at the optimum; P5: grain filling phase duration ($^{\circ}\text{C}\cdot\text{d}$); G1: Kernel number per unit canopy weight at anthesis ($\#/g$); G2: standard kernel size under optimum conditions (mg kernel^{-1}); G3: standard, non-stressed dry weight of a single tiller at maturity (g tiller^{-1}); PHINT: interval between successive leaf tip appearance ($^{\circ}\text{C}\cdot\text{d}$).

Soil Data

The predominant soil type at the Lahoma station was a Grant silt loam (fine-silty, mixed, superactive, thermic Udic Paleustolls). A measured soil profile on the Oklahoma Mesonet site at the Lahoma station was used in the simulation (<http://www.mesonet.org/sites>). The soil in the top 0.3 m comprised of approximately 24% clay and 53% silt. The major soil type at the Marshall station was a Kirkland silt loam soil (fine, mixed, superactive, thermic Udic Paleustolls). A detailed soil profile measured at Stillwater (approximately 45 km east of Marshall), which was representative of the series in the region, was used for simulation at Marshall. The top 0.3-m soil contained about 30% clay and 43% silt. At the Chickasha station, the prevalent soil type is a McLain silt loam (fine, mixed, superactive, thermic Pachic Argiustolls). A typical soil profile for the series, which had 16% clay and 45% silt in the top 0.3 m, was chosen from the NRCS-Soils 5 database (<http://soils.usda.gov>). For all three soil series, bulk density, field capacity (upper drainage soil water), and wilting point soil moisture were taken from measured values for similar soils in the study region, and a profile depth of 1.4 m were used in the simulation.

Daily Weather Data

Daily weather data (maximum and minimum temperature, daily precipitation, and solar radiation) measured at Oklahoma Mesonet sites at the Chickasha, Lahoma, and Marshall stations since 1994 were used to compile the weather input file for the model (<http://www.mesonet.org>). Prior to 1994, daily maximum and minimum temperatures and daily precipitation were measured on the Chickasha and Lahoma sites of the National Weather Service Coop stations and were directly used in the weather input files (<http://climate.ok.gov>). However, only daily precipitation was measured on the Marshall site, and daily maximum and minimum temperatures were taken

from the Stillwater station (about 45 km east of Marshall). Daily solar radiation was not measured at any of the three stations prior to 1994, and the daily weather generator of WGEN (Richardson, 1981) within the DSSAT model was used to fill the missing data using the statistics derived from the Mesonet daily radiation records of 1994-2006 at each station.

Calibration of Crop Coefficients

Crop genetic coefficients for the TAM 101 and Jagger varieties were calibrated in this study using wheat growth data measured at El Reno in central Oklahoma during 2004-2006. The field measurements included phenological development stages, leaf area index, canopy top biomass, grain yield, individual grain weight, grain number per unit area. Those data were used to calibrate the five crop coefficients for the semidwarf TAM 101 and Jagger varieties for the DSSAT wheat model (Table 5). The calibrated coefficients were used in simulation for all three locations, except that P1V=42 and P1D=70 for Jagger were used for the grazing study at Marshall to ensure that first hollow stem appeared after the termination of grazing for all varieties. In the model calibration, we have found that simulated canopy top weights (above ground biomass) differed by as much as 30% among the three different ET methods available in DSSAT. The Priestley-Taylor (1972) method, which does not require wind velocity and relative humidity, was used in all simulations in this work because of the lack of wind velocity and relative humidity measurements before 1994.

Model Performance Measures

Model predictability was evaluated by calculating the mean percentage absolute error (MPAE), mean percentage error (MPE), root mean square error (RMSE), and model efficiency (ME) of Nash and Sutcliffe (1970) as:

$$MPAE = \left[\sum_{i=1}^n \left(\frac{|Y_i - X_i|}{X_i} \right) 100 \right] / n$$

$$MPE = \left[\sum_{i=1}^n \left(\frac{Y_i - X_i}{X_i} \right) 100 \right] / n$$

$$RMSE = \left[\left(\sum_{i=1}^n (Y_i - X_i)^2 \right) / n \right]^{1/2}$$

$$ME = 1 - \frac{\sum_{i=1}^n (Y_i - X_i)^2}{\sum_{i=1}^n (X_i - \bar{X})^2}$$

Where Y_i is the predicted value, X_i is the observed value, \bar{X} is the observed mean, and n is the number of observations. The MPE and MPAE are the means of relative errors and absolute relative errors between prediction and measurement, respectively. The RMSE represents the mean distance between prediction and measurement. A zero value of MPAE or RMSE indicates the perfect prediction for each observation. The ME can vary from $-\infty$ to 1. If ME equals 1, the model produces the exact prediction for each observation. A value of zero implies that a single mean measured value is as good an overall predictor as the model. A negative value indicates that the measured mean is a better predictor than the model.

RESULTS AND DISCUSSION

Variety Trials

The crop coefficients calibrated for the TAM 101 and Jagger varieties at El Reno were used to simulate forage and grain yields at Chickasha and Marshall. For a cutting height of 50-64 mm, 1000-kg ha⁻¹ canopy top biomass was assumed left standing after cutting, based on an independent field measurement conducted in late November in 2006 at El Reno. This estimate was very crude, because the standing top biomass left after cutting varied with tiller numbers and size, which were determined not only by environmental factors but also by planting and clipping dates. Simulated forage yield for the first clipping was simply the difference between simulated canopy top biomass at the date of clipping and the 1000-kg ha⁻¹ threshold. For simulating forage regrowth (2nd and 3rd clippings), wheat pasture was grazed down to approximately 1000-kg ha⁻¹ standing biomass by grazing a predetermined number of stockers for one day at the previous cutting date, and the difference in simulated canopy weights between the two clipping dates was used as the regrowth estimate. The measured forage yields (Tables 1 and 2) are plotted with the corresponding simulated values in Fig. 1. The overall MPAE, MPE, and RMSE were 52.7%, 24.3%, and 815.0 kg ha⁻¹, respectively. The ME for all measurements in Fig. 1 was 0.102, which was relatively small, indicating that the model's predictive ability in simulating fall-winter forage yields was relatively low for the experiment datasets at the two locations. Specifically at Chickasha, the model predicted forage regrowth much better than the forage yields of the first

clippings. In contrast, the fall forages were better predicted than the winter forages at Marshall, except for the fall forage on 15 Dec. 1996 (Fig. 1). The measured low fall forage yield in 1996 was caused by a severe leaf rust infestation that had destroyed the lower leaves by mid-November at the site due to wet conditions (Krenzer et al., 1996). On the other hand, disease and pest damage was not simulated in the wheat model, and the ample rainfall in the fall made the model overpredict forage production.

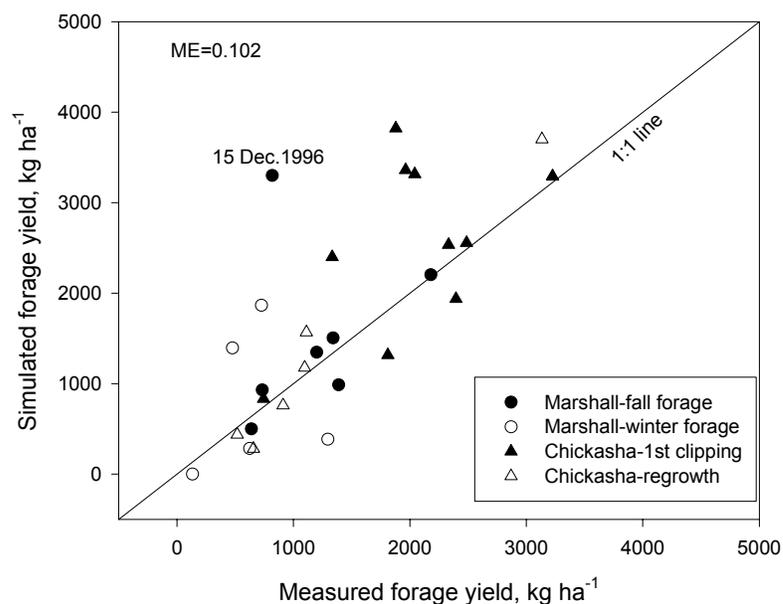


Fig. 1. Simulated and measured fall-winter forage yields of the TAM 101 and Jagger varieties in the variety trial experiment at Marshall and Chickasha, OK (fall forage: forage production before 31 December; winter forage: forage production from 1 January to early March).

A preliminary analysis for conditions in central Oklahoma showed that forage production was sensitive to initial soil moisture and N status as well as to timing of N application if N was limitative. As presented in the method section, a generic set of the initial soil moisture conditions and a rigid scheme of N application were used in the simulation, largely because most of the relevant information was unavailable. If more detailed information was known, model prediction could have been improved. Another potential source of error was the assumption of

the 1000-kg ha⁻¹ biomass threshold value. This value definitely changed from year to year for the reasons discussed earlier.

The measured grain yields from both dual-purpose wheat and grain-only wheat of the variety trials (Tables 1 and 2) are plotted against the simulated grain yields at Chickasha and Marshall in **Fig. 2**. The model predicted wheat grain yields better than it predicted fall-winter forage production.

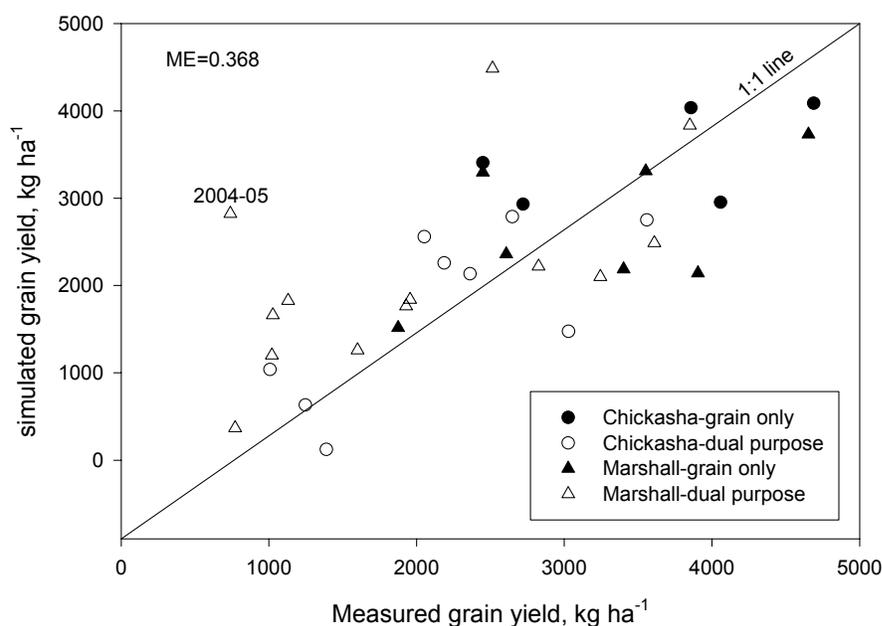


Fig. 2. Simulated and measured grain yields of TAM 101 and Jagger for both dual-purpose and grain-only winter wheat in the variety trial experiment at Marshall and Chickasha, OK.

The overall MPAE, MPE, and RMSE were 35.3%, 1.4%, and 887.3 kg ha⁻¹, respectively. The ME for all the data points in Fig. 2 was 0.367. For the dual-purpose wheat at Marshall, the measured grain yield for the 2004-2005 season was much lower than the simulated yield. The low measured yield resulted from the severe damage caused by cattle traffic under extremely wet or even waterlogged conditions due to excessive rainfall in the fall and winter. In general, the measured grain yields from grain-only wheat were higher than those of the dual-purpose wheat (Tables 1 and 2). For the years having both treatments, the measured yields for dual-purpose wheat were, on average, 30% and 17% lower than those for the grain-only wheat at Chickasha and Marshall, respectively. Comparatively, the simulated mean grain yield of dual-purpose

wheat was about 29% lower than that of grain-only wheat at Chickasha, while it was 7% higher at Marshall. The slightly higher grain yields in the dual-purpose wheat system than in the grain-only system at Marshall might have resulted from differences in fertilization rates and planting dates as well as the uses of a lighter stocking rate and shorter grazing periods in the simulation. Similar to forage prediction, if better model input data were available, the prediction could possibly be even better.

Planting Date Field Trial

More than a dozen different varieties were planted during the 9-year experiment (Table 3). Though we do not have complete information on what varieties were grown in which year, we do know they were semidwarf, early maturity varieties commonly grown in the region. As the first order assessment, the calibrated crop coefficients of the variety Jagger being representative of the group were used in simulation. To better reflect data variability or uncertainty, all data points including all varieties and replicates along with simulated values are plotted in **Fig. 3** for wheat forage production. One-day simulated grazing was used to mimic the clipping. Standing wheat biomass left in the field after each grazing was assumed to be approximately 1500 kg ha^{-1} , based on the target clipping height of about 80 mm. Wheat was grazed on 15 December for harvesting fall forage and for subsequent estimation of winter regrowth, and on 10 February for estimating grain yield. The model consistently over predicted fall-winter forage yields with the default root downward extension rate of 30 mm d^{-1} (**Fig. 3**). Most simulated values for most years and most planting dates were above the upper bound of all varieties. Since sufficient N fertilizer was applied at planting and low temperature stress was unlikely due to early planting, the overestimation of forage yield might have been caused by lesser water stress. To test this speculation, a root downward extension rate of 20 mm d^{-1} was used to elevate water stress in fall and winter. The simulated forage yields were greatly decreased as expected, and were within the measured ranges for most years and planting dates (Fig. 3). The mean percentage absolute error (MPAE), mean percentage error (MPE), and root mean square error (RMSE) were 221%, 205%, and 1647 kg ha^{-1} , respectively, at the 30-mm d^{-1} rooting rate; while they were correspondingly 92%, 72%, and 720 kg ha^{-1} at the 20-mm d^{-1} rooting rate.

Simulated grain yields under both root downward extension rates are shown in **Fig. 4**.

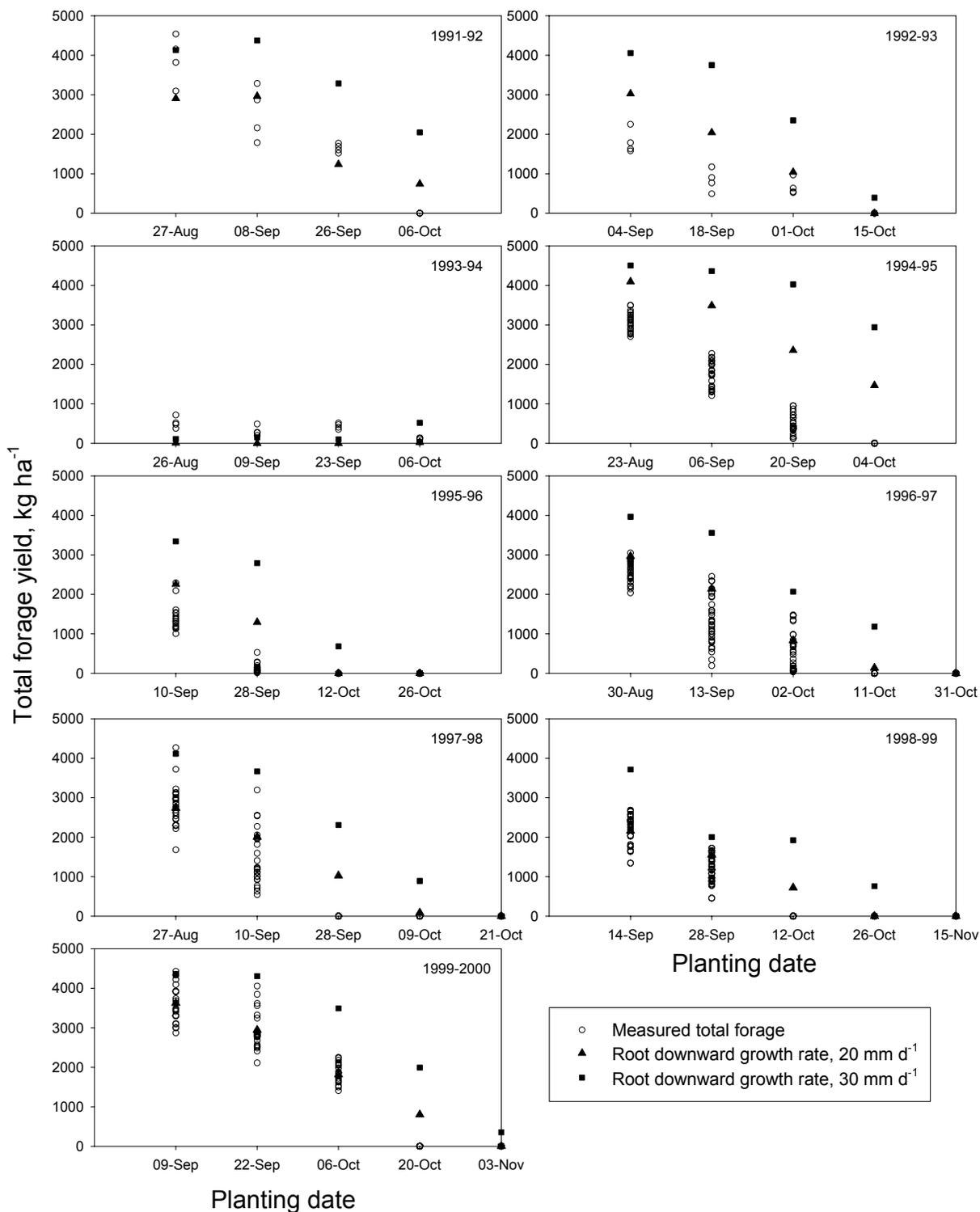


Fig. 3. Simulated and measured total fall-winter forage yields as a function of planting dates for all varieties in the planting date experiment at Lahoma, OK. Measured data were taken from Hossain et al. (2003).

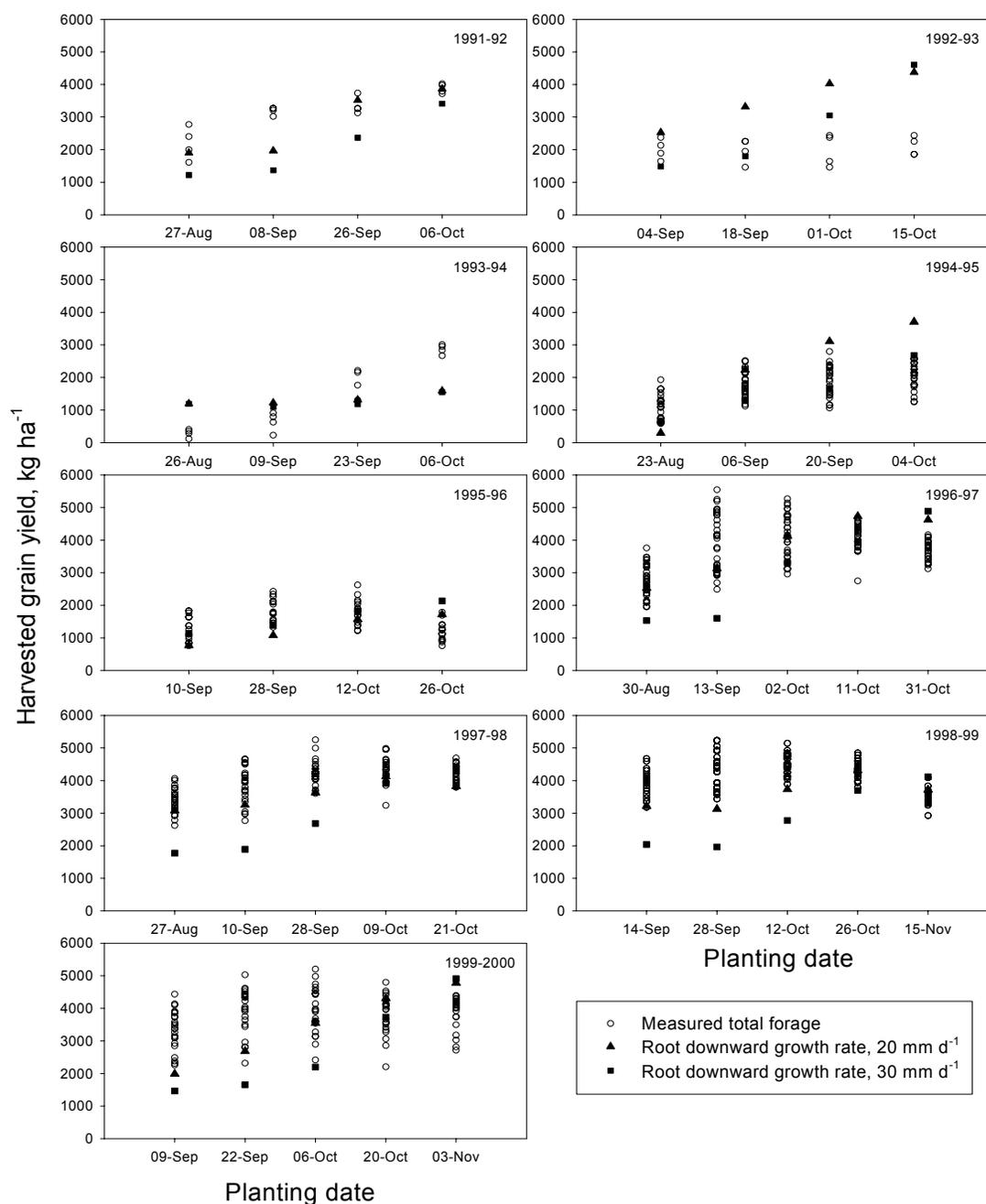


Fig. 4. Simulated and measured grain yields as a function of planting dates for all varieties in the planting date experiment at Lahoma, OK. Measured data were taken from Hossain et al. (2003).

The simulated grain yields, especially at early planting dates, were lower than the lower bound of measured grain yields for five out of nine years at the 30-mm d⁻¹ rooting rate. However, the simulated grain yields were considerably increased at the 20-mm d⁻¹ rooting rate and were within the measured ranges for most planting dates. The increase in grain yields at 20 mm d⁻¹ was the

results of the reduced water use at the early vegetative growth stages and increased water availability at the reproductive stages. The MPAE, MPE, and RMSE for grain yields were 43%, -5.3%, 1246 kg ha⁻¹, respectively, at the 30-mm d⁻¹ rooting rate; while they were 39%, 12.5%, and 902 kg ha⁻¹ at 20 mm d⁻¹. Overall, both fall-winter forage and grain yields were better simulated at the 20-mm d⁻¹ rooting rate than at the 30-mm d⁻¹ rooting rate, compared with the measured data. This result indicated that seasonal water use by wheat was better simulated at the 20-mm d⁻¹ rooting rate. The slower root extension rate may be justified by greater penetration resistance below the tillage layer in the region. In addition, the low forage and grain yields of the 1993-1994 and 1995-1996 crop years, resulting from dry conditions of below normal precipitation, were relatively well simulated by the model.

The measured and simulated total forage and grain yields are shown in **Fig. 5**. The data points for both forage and grain yields at the 20-mm d⁻¹ rooting rate were closer to the 1:1 line than those at the 30-mm d⁻¹ rooting rates. The model efficiency (ME) for forage prediction was 0.615 with the 20-mm d⁻¹ rooting rate and was -1.017 with the 30-mm d⁻¹ rooting rate for all data points; while it was 0.824 and -0.354 without the data of the 1992-1993 and 1994-1995 seasons. The ME for grain yield prediction was 0.409 at the 20-mm d⁻¹ rooting rate and was -0.127 at the 30-mm d⁻¹ rooting rate for all data points; while it was 0.627 and -0.240 without the data of 1992-1993 and 1994-1995. The exclusion of the two crop seasons was because of a severe leaf rust infestation in 1992-1993 and a root rot disease in 1994-1995 and an unseasonal cold front around April 10 in 1995, which decreased the measured forage and grain yields considerably. There were large variabilities in the measured wheat forage and grain yields among the varieties (Figs. 3 and 4). The differences among sample replicates were quite large too. For example, for the 1991-1992 crop year in which Karl was the only variety grown, considerable differences in the forage and grain yields between the four replicates were exhibited, especially for the early planting dates. Considering that the inherent variability existed in the measured data and that the model was only calibrated to one variety, the predicted results were satisfactory in that the effect of planting date and climate variation on forage and grain yields was reasonably represented by

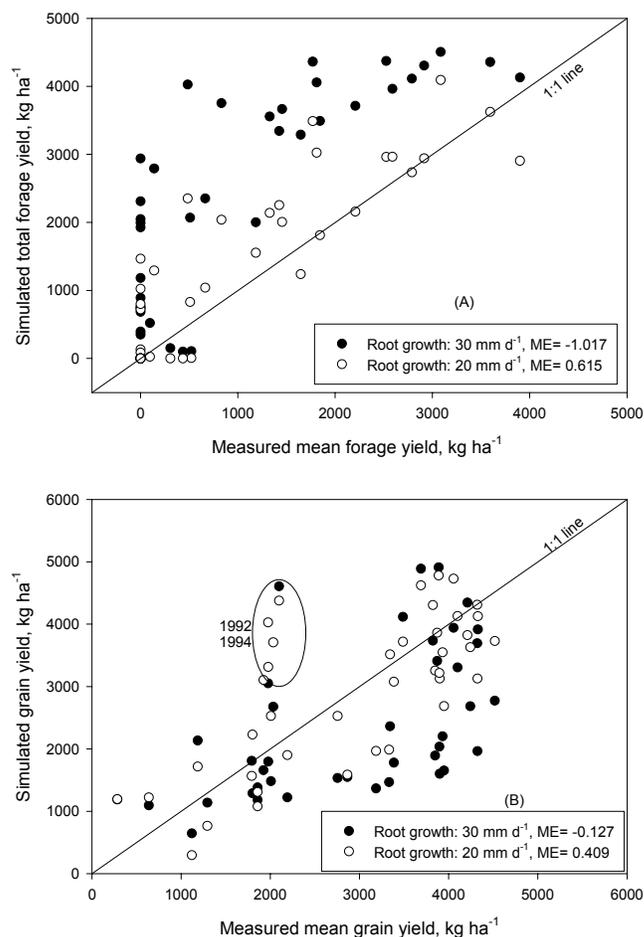


Fig. 5. Scatter plots of simulated vs. measured values for total forage yields (A) and grain yields (B) at the two root downward advance rates for all varieties of the planting date experiment at Lahoma, OK.

the model. Should more detailed input data such as initial soil conditions, soil properties, timing of fertilization and clipping, and crop coefficients of particular varieties be available and used, model predictions would likely to be improved.

Dual-purpose Wheat and Steer Grazing Trials

The crop coefficients of the Jagger variety in Table 5 were used to simulate all varieties. An adjusted value of 42 for PIV and 70 for PID were used to delay the early phenological development stages so that the simulated dates of first hollow stem appearance were later than the grazing termination dates of Table 4 for most varieties to satisfy the fact that the grazing was terminated before first hollow stem. To better evaluate the cattle growth algorithm (in particular,

the response of cattle weight gain to forage availability), the simulated mean standing wheat biomasses during the grazing periods were matched to the observed means at the lightest stocking rate for each variety in each year (Table 4) by varying the radiation use efficiency before the flag leaf stage [expressed in grams of dry matter (DM) produced per MJ energy]. The radiation use efficiency after the last leaf stage (2.8 g MJ^{-1}) was not changed. The calibrated values at the lowest stocking rates, typically ranging from 2.2 to 3.1, were used in simulations for the remaining stocking rates within each variety and year.

Measured and simulated relationships between average daily weight gain and forage allowance [defined as dry forage matter per 100-kg body weight (BW)] are shown in **Fig. 6**.

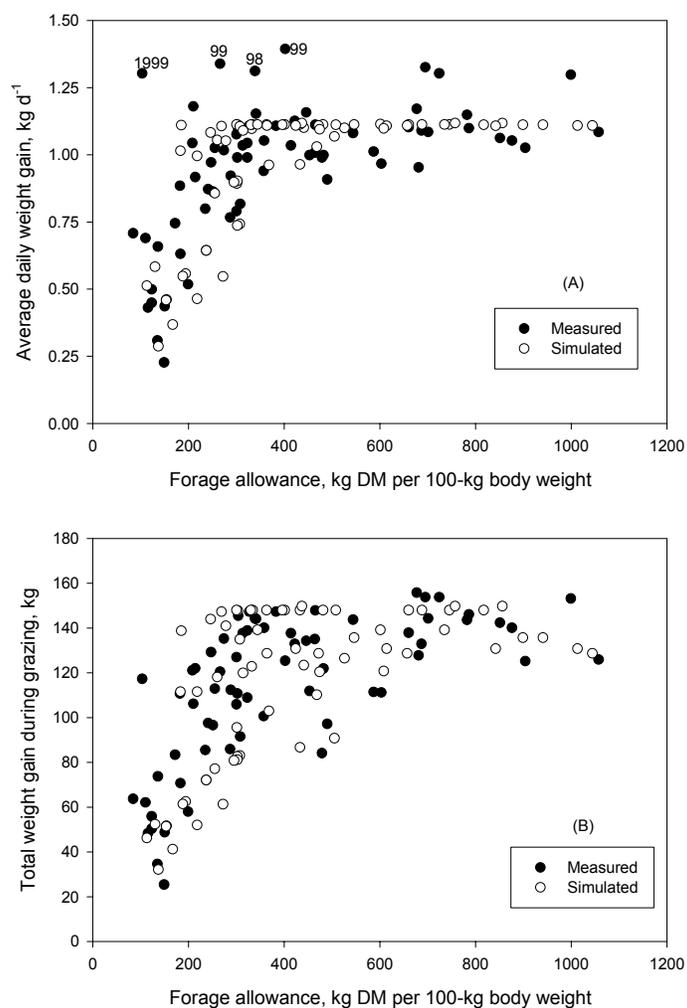


Fig. 6. Simulated and measured relationships between average daily weight gain and forage allowance (A) and between total weight gain and forage allowance (B) of the dual-purpose wheat and steer grazing experiment at Marshall, OK.

Forage allowance reflects a combined effect of forage availability and stocking rates, and therefore is a good indicator of grazing pressure. Stocking rates remained constant during the grazing seasons before 1993-1994, but were adjusted according to target forage allowance to ensure constant grazing pressure afterwards. The measured forage allowance ranged from 84 to 1057 kg DM per 100-kg BW, and the simulated ranges were between 113 and 1044. Obviously, a threshold forage allowance value existed in Fig. 6A. Both measured and simulated average daily weight gains increased rapidly in a somewhat linear fashion with forage allowance below the 400 threshold, and remained more or less constant above the threshold. The scattering of the measured data points below the threshold was well mimicked by that of the simulated data. The simulated average daily weight gains asymptotically approached 1.12 kg d⁻¹ for forage allowance of greater than 400, while the measured values fluctuated between 0.91 and 1.39 with a mean value of 1.10 kg d⁻¹. The measured average daily weight gains ranged from 0.227 to 1.394 kg d⁻¹. Comparably, the simulated values ranged from 0.287 to 1.118 kg d⁻¹. There were three cases where the average daily weight gains were greater than 1.30 kg d⁻¹ when the season-averaged forage allowances were about 103, 266, and 339 kg DM per 100-kg BW. There were no satisfactory explanations for such great daily weight gains at such low forage allowances. One possible cause could be the sampling error in measuring forage biomass due to large spatial and temporal variations. Sampling three to four times at a few locations during the grazing periods was prone to estimation error. Total weight gain during a grazing season is a function of grazing duration and average daily weight gain that is further related to forage allowance (Fig. 6A). Relationship between total weight gain and forage allowance is presented in Fig. 6B. The scattering of the simulated data points matched that of the measured data points relatively well, showing reasonable agreement and correspondence between measured and simulated data.

Measured total weight gains per steer were well simulated by the model for the wide ranges of grazing days and stocking rates (**Fig. 7**). The grazing days ranged from 85 to 134, and the stocking rates varied from 0.84 to 2.87 head ha⁻¹ in the entire experiments. The overall MPAAE, MPE, and RMSE for all data points were 18.1%, 5.6%, and 20.2 kg steer⁻¹, respectively. The ME was about 0.616 for all data points, and 0.686 without the 2.05-head ha⁻¹ stocking rate for the variety 2163 in 1992-1993, where the measured weight gain was 25.4 kg while the simulated value was 111.6 kg. The overprediction for the weight gain resulted directly from the

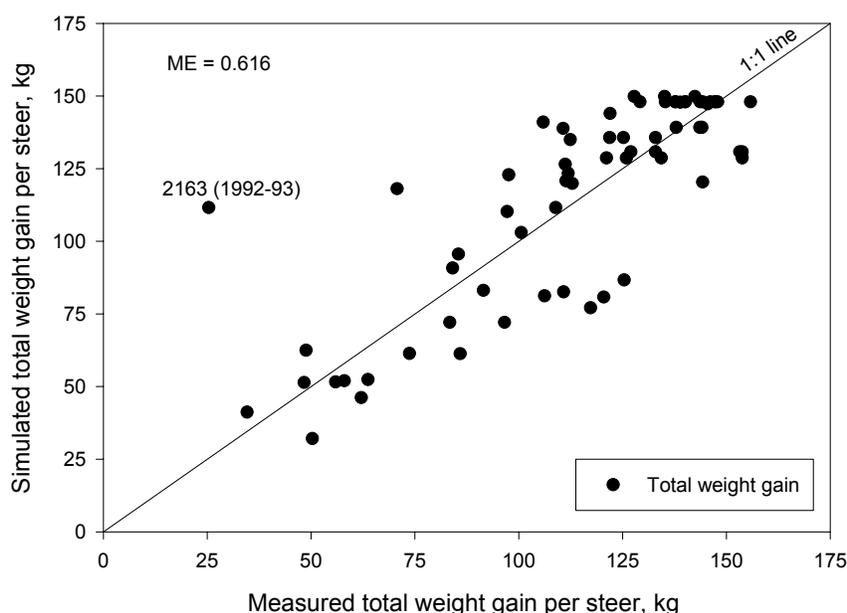


Fig. 7. Scatter plot of simulated vs. measured total steer weight gain during the entire grazing season in the dual-purpose wheat and grazing experiment at Marshall, OK.

overestimation of forage availability for the 2163 variety during 1992-1993. The simulated season-average wheat forage was about 1219 kg ha^{-1} , while the measured value was only 702 kg ha^{-1} .

The model consistently overpredicted the grain yields of the grazed winter wheat. The overall measured mean was 1851 kg ha^{-1} , while the predicted mean was about 2849 kg ha^{-1} . Due to the gross overprediction, the ME was negative, indicating that the measured mean was a better predictor than the model. Though grain yield prediction could be improved by better calibration to each individual variety and by using more soil-specific data, the results might indicate a possibility that the model has a tendency to overpredict grain yields under grazing conditions. A probable cause might be that the physical damage caused by cattle trafficking and trampling is not considered in the model. More research is needed before this process can be appropriately quantified and incorporated into the model.

SUMMARY AND CONCLUSIONS

One-day heavy grazing was used to mimic forage clipping to estimate forage growth and regrowth following clipping in the variety trials. The model simulated forage regrowth better

than forage yields of first clippings at Chickasha; however, the model predicted fall forage better than winter forage at Marshall except for one measurement. The overall ME for all data points was 0.102, which was relatively low but could possibly be improved if better model input data were available. The model predicted wheat grain yields better than it predicted fall-winter forage production. The overall ME including both dual-purpose and grain-only wheat was 0.367, indicating the model's ability to simulate the effect of wheat grazing or clipping on grain yields.

For the planting date trial, the model consistently overpredicted fall-winter forage production and underpredicted grain yields when the default root downward extension rate of 30 mm d⁻¹ was used. However, when a rooting rate of 20 mm d⁻¹ was used, both forage and grain yield predictions were improved (i.e., forage decreased while grain increased), with ME increased from negative to 0.615 for the former and from negative to 0.409 for the latter. The reasons for decreasing forage production and increasing grain yield were that the slower rooting rate exerted more water stress in the early vegetative growth stages and consequently conserved more soil moisture for use in the reproductive stages. Given large variation existed in the measured data between varieties, a better calibration to individual varieties would improve the model's performance.

The relationship between average daily weight gain and forage allowance was adequately represented by the model under a wide range of stocking rates and climate conditions. A threshold forage allowance of 400 kg DM per 100-kg BW was identified in both measured and simulated data. Average daily weight gain increased rapidly with forage allowance below 400, and remained somewhat constant above 400 with the measured and simulated means being 1.10 and 1.12 kg d⁻¹, respectively. The total weight gains per steer during entire grazing periods were well simulated (ME=0.616). The measured total weight gains ranged from 25 to 156 kg per steer, and simulated gains ranged between 32 and 150 kg.

Overall results show that the model has the potential to predict fall-winter forage production and grain yields of both dual-purpose and grain-only winter wheat. The model simulated daily steer weight gain satisfactorily well if forage availability was adequately simulated. Model's ability to predict forage and grain yields can be improved if it is well calibrated and better input data are provided.

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