Tillage and Cattle Grazing Effects on Soil Properties and Grain Yields in a Dryland Wheat–Sorghum–Fallow Rotation

R. L. Baumhardt,* R. C. Schwartz, J. C. MacDonald, and J. A. Tolk

ABSTRACT

Cattle (*Bos taurus*) grazing intensifies production of the dryland wheat (*Triticum aestivum* L.)–sorghum [*Sorghum bicolor* (L.) Moench]–fallow (WSF) rotation in the U.S. Southern High Plains. Stubble-mulch (SM) tillage controls weeds and counteracts soil compaction. No-till (NT) increases soil water at planting and dryland crop yields, but added grazing effects are unknown. Our objectives were to quantify dryland winter wheat and sorghum yield responses to grazing and tillage practices. At the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX, we established all WSF rotation phases in triplicate ungrazed and grazed paddocks beginning 1999 on a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) using SM tillage. During spring 2004, NT or SM tillage were superimposed within grazing main plots. Cattle gain, soil water after fallow, and crop yield were compared during 2005 to 2009 using a split-plot randomized complete block design. Cattle, stocked at 1.8 Mg ha^{-1}, grazed sorghum stover and growing wheat an average of 29 d for a mean gain of 147 kg ha^{-1}. Soil water at planting was unaffected by grazing, but increased from 14 to 28 mm with NT. Although grazing seldom reduced yield of wheat or sorghum, NT in ungrazed plots increased crop yields sufficiently (0.96–2.6 Mg ha^{-1}) in 2008 and 2009 to offset any value added by grazing. We conclude that cumulative grazing effects in NT plots reduced soil water storage and depressed yield. We recommend post-wheat-harvest SM tillage to disrupt soil compaction and restore grazed soil productivity.

Irrigated land in the Texas High Plains has decreased from a peak of 2.42 million ha in 1974 to 1.87 million ha in 2000 due, in-part, to the declining Ogallala Aquifer that supplies the irrigation water (Colaizzi et al., 2009). Water in sufficient quantities to support irrigation and profitability of crops for this region may not be available in similar amounts as in prior years (Allen et al., 2005); therefore, continued success of southern High Plains agriculture will require intensification of dryland cropping systems to increase profitability. For example, Decker et al. (2009) reported for rainfed production systems near central Oklahoma receiving ~800 mm annual precipitation, that grazing wheat grown for forage or dual purpose forage and grain increased profitability over the corresponding grain-only system.

One sustainable dryland cropping system commonly used on the more arid southern High Plains region is wheat grown in rotation with grain sorghum on ~450 mm of annual precipitation (Baumhardt and Salinas-Garcia, 2006). This WSF rotation (Fig. 1) begins during September of the first year with planting of winter wheat that is harvested for grain in July. Grain sorghum is planted 11 mo later in June of the second year, grown on stored soil water plus rain, and harvested for grain in November. The land is, subsequently, fallowed through the summer of the third year to permit storage of precipitation as soil water when wheat is planted and the rotation cycle is repeated. Producers often manage multiple fields with the WSF rotation so that all three phases appear during any 1-yr period, which permits simultaneous grazing of both growing wheat forage and stover remaining after sorghum harvest but not wheat straw. This rotation utilizes the soil water stored during fallow plus seasonal precipitation to produce two dryland grain crops in a 3-yr cycle with a 10-yr mean grain yields of 3.7 Mg ha^{-1} for sorghum and 1.5 Mg ha^{-1} for wheat (Jones and Popham, 1997). The corresponding annualized yield of this 3-yr rotation, calculated as the mean annual yield divided by 3, was 1.23 Mg ha^{-1} for sorghum and 0.5 Mg ha^{-1} for wheat that combine for an overall rotation annualized mean grain yield of 1.73 Mg ha^{-1}. Baumhardt et al. (2009) intensified that dryland WSF rotation by integrating cattle to graze dual purpose wheat forage and nearby sorghum stover for 31 d to increase profitability and provide a possible transition from irrigated to dryland cropping systems where the fallow phase was maintained with SM tillage.

Several studies have demonstrated the viability of grazing wheat established under rainfed conditions (Redmon et al., 1995; Russelle et al., 2007) or when using irrigation in lieu of timely rain for wheat establishment and growth in semiarid regions (Winter, 1994). Conservation tillage with SM and NT may increase precipitation storage during fallow sufficiently to improve establishment and growth of wheat. For a 1.8-m Pullman soil profile, the 10-yr average available water at wheat planting increased approximately 10% from 183 mm for SM to 200 mm with NT because of less evaporation (Jones and Popham, 1997). Reduced evaporation during fallow with residue retaining conservation

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Abbreviations: NT, no-tillage; PR, penetration resistance; SM, stubble-mulch tillage; WSF, wheat–sorghum–fallow rotation.

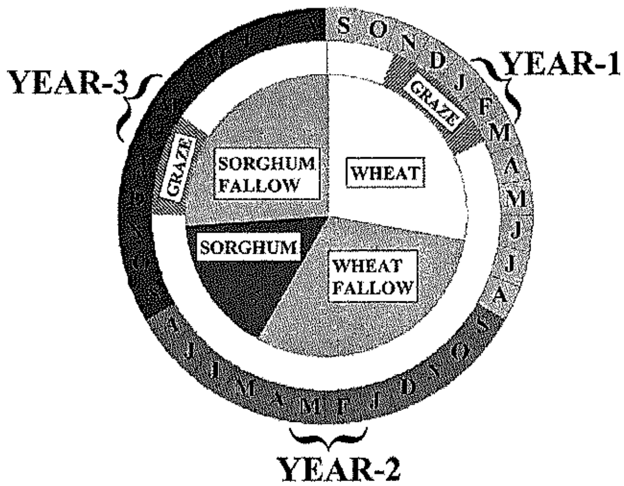

Fig. 1. The wheat–sorghum–fallow (WSF) crop rotation is diagrammed as a repeating 3-yr sequence beginning in September with wheat planting. Vegetative wheat growth during this first phase can provide forage as early as November in Year 1 in combination with post-grain-harvest sorghum stover available during the fallow after the sorghum rotation phase in Year 3. Grazing of sorghum stover and vegetative wheat growth during our study was delayed after January and continued into March.

tillage practices typically increases soil water storage and translates to greater crop yield (Unger et al., 2010). Because NT provides no mechanism to disrupt the soil, Winter and Unger (2001) reported surface soil compaction with grazing cattle that reduced irrigated wheat residue and decreased subsequent grain yield of dryland sorghum grown in the WSF rotation. In another study by Bari et al. (1993), rain infiltration was reduced because trampled soil had greater density and because more bare soil was exposed to raindrop impact if cattle consumed 25 to 30% of the sorghum residue. Surface soil density and crop residue can govern the infiltration and storage of precipitation as soil water, which is critical for sustaining dryland crop yields in semiarid regions.

Winter and Unger (2001) evaluated tillage and grazing effects on crop yields of dryland sorghum grown after irrigated wheat; however, we found no similar study quantifying tillage and grazing effects on the growth and yield of dryland wheat and grain sorghum grown under semiarid conditions. We hypothesized that integrated crop–livestock production systems sustain soil compaction due to trampling. This soil compaction is counteracted by conventional SM tillage but develops with NT, which reduces crop yield and profitability of the WSF rotation used in semiarid dryland production. Our objectives were to quantify the effects of grazing followed by conventional or NT management on the growth and yield of the grazed wheat and subsequent sorghum crops.

MATERIALS AND METHODS

We quantified the effects of cattle grazing and tillage on crop forage and grain yields for dryland WSF cropping systems at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX (35°10.25′ N, 102°5′ W) by modifying an ongoing experiment begun in 1999 (Baumhardt et al., 2009). In that experiment, a 330-m-wide by 500-m-long (16.5 ha) field of gently sloping (1.5%) Pullman clay loam was divided into three blocks to control variation from slope. For each block, grazed or ungrazed main plot treatments were randomly assigned in two 165-m-wide paddocks that included all three WSF rotation phases in randomly assigned 55-m-wide SM plots. Beginning in 2004, NT or SM tillage treatment splits were superimposed on 27.5-m subplots within all previously SM tillage phases during the idle or fallow periods preceding planting of crops harvested in 2005. Although all WSF phases of this 3-yr rotation appear each year to maximize tillage and grazing treatment comparisons for this 5-yr study, repeated observations from unique experimental units only occur every third year.

British by European-exotic crossbred steers weighing approximately 0.25 Mg were stocked in electrically fenced paddocks at a target rate of 1.8 Mg ha^{-1} (wheat area) depending on available wheat forage, but usually in mid-February. Cattle grazed the entire paddock, including plots with sorghum stover, until wheat forage became insufficient to maintain gain; however, we terminated grazing before seed head formation as signaled by hollow stem development in ungrazed wheat (Redmon et al., 1996). Cattle gain was calculated as the difference between stocking and pull-off mass, determined after 1-d shrinkage, and related to the grazed wheat area.

Agronomic

As described by Baumhardt et al. (2009), winter wheat (cv. TAM-110, Foundation Seed, College Station, TX)[1] was sown with a high-clearance grain drill to obtain 200 plants m^{-2} (~50 kg ha^{-1} sowing rate) in rows 0.3-m apart during early September to late October when soil water was adequate for wheat establishment. Seasonal broadleaf weeds were controlled in wheat typically in the spring using 0.6 kg a.i. ha^{-1} 2,4-D [(2,4-dichlorophenoxy) acetic acid] following grazing as recommended when using synthetic auxins on pastures (Hartzler and Owen, 2005). Wheat was harvested in July and plot areas remained idle for approximately 11 mo until mid-June when grain sorghum, Pioneer hybrid 8699 (Pioneer Hi-Bred Intl., Johnston, IA), was seeded in 0.75-m rows at 8.0 seeds m^{-2}, using 'Max-Emerge' (John Deere, East Moline, IL) unit planters. Sorghum seed was safened with fluxofenim [1-(4-chlorophenyl)-2,2,2-trifluoroethanone O-(1,3-dioxolan-2-ylmethyl)oxime] for use with commercially available mixtures of atrazine [6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2,4-diamine] and metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide] that were applied preemergence at rates of 1.3 kg a.i. ha^{-1} and 1.0 kg a.i. ha^{-1}, respectively, for seasonal weed control. Grain sorghum was harvested at maturity during November and the plots were fallowed approximately 10 mo until September when wheat was planted and the rotation repeated. No supplemental N fertilizer was required to meet expected dryland yields of wheat or grain sorghum because the needed 50 kg ha^{-1} N is mineralized between crops in this rotation (Eck and Jones, 1992; Jones et al., 1997). Because the Pullman clay mineralogy supplies sufficient K to meet crop demand (Johnson et al., 1983) and dryland crop response to broadcast applied P fertilizer has been limited (Eck, 1969, 1988), no P or K fertilizers were applied.

During the idle period following wheat harvest or the fallow after sorghum harvest, either SM or NT residue management was maintained. On demand SM weed control (3–4 tillage

[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

operations) was performed using a 4.6-m-wide Richardson (Sunflower Man. Co., Inc., Beloit, KS) sweep-plow operated at a depth of 0.10 m. For NT, chemical weed control used both contact and soil active herbicides as governed by chemical residual and subsequent crop sensitivity. Specifically, we applied 1.1 kg ha^{-1} a.i. atrazine tank mixed with 0.84 kg ha^{-1} a.i. 2,4-D after wheat harvest for weed control during the idle period between the wheat harvest and sorghum establishment. During fallow after sorghum, 0.37 kg a.i. ha^{-1} 2,4-D plus a commercially available premix of 0.006 kg ha^{-1} a.i. chlorosulfuron ((2-chloro-*N*{[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino] carbonyl} benzenesulfanomide)) and 0.011 kg a.i. ha^{-1} flucarbazone-sodium ((4,5-dihydro-3-methoxy-4-methyl-5-oxo-N-{[2-(trifluoromethoxy)phenyl]sulfonyl}-1H-1,2,4-triazole-1-carboxamide, sodium salt)) were applied in the spring for weed control until wheat establishment. Any weed escapes during these times were controlled with applications of 0.56 kg a.i. ha^{-1} glyphosate [N-(phosphonomethyl) glycine].

Measurements

Precipitation was obtained from the location official standard rain gauge. Soil water content was sampled gravimetrically to a depth of 1.8 m taken in 0.3-m increments using two soil cores at planting (after fallow) and three soil cores at harvest to better control variability. Volumetric soil water was calculated from these gravimetric samples and a single previously measured uniform soil density for both SM and NT according to Jones et al. (1994) and reported as plant-available soil water (water held between 0.03 and 1.5-MPa matric water potential). Precipitation storage during fallow was computed as the difference in initial soil water content at harvest and planting of the subsequent crop. Soil penetration resistance (PR) during fallow after wheat or sorghum was measured in 2007 at three equidistant plot locations for each tillage and grazing combination using a digital penetrometer (Field Scout, SC 900 Soil Compaction Meter; Spectrum Technologies, Inc., Plainfield, IL) that recorded observations in 0.025-m intervals to a depth of 0.45 m.

We measured starting wheat forage and sorghum stover amounts using triplicate oven-dried 0.76-m^2 hand samples harvested from each plot immediately after cattle stocking. Similarly, triplicate wheat seed-head number, seed mass, and grain yield samples were hand-harvested from a 0.76-m^2 area from all wheat plots. Wheat grain yield was standardized to 120 g kg^{-1} water content (wet basis). Sorghum seed head number, seed mass, and grain yield, standardized to 130 g kg^{-1} water content (wet basis), were determined at crop maturity from triplicate 1.54-m^2 hand-harvested samples. In 2009, we determined total elemental N from ground sorghum grain yield samples using dried combustion and subsequent thermal conductivity analyses of evolved gases with a Vario Max CN analyzer (Elementar, Hanau, Germany) as described by Schwartz and Dao (2005).

Soil parameters, and wheat and sorghum yield and growth factors were analyzed according to a split plot randomized complete block design using SAS mixed linear models ANOVA procedures (SAS Institute, 2004). The 2009 PR observations were, likewise, analyzed according to that split plot design procedure for each depth increment. Our preliminary analyses identified significant year effects and heteroscedastic experimental errors probably because of variable growing season conditions such as precipitation. We, therefore, analyzed tillage and grazing treatment effects on dependent parameters within years for both wheat and grain sorghum.

RESULTS AND DISCUSSION

Quantifying crop growth and yield in response to grazing and tillage practices was our primary objective; nevertheless, cattle gain performance from grazing during the years 2005 through 2009 remained fundamental to this integrated production system. Under semiarid dryland production conditions, fall wheat growth was slow and delayed production of adequate forage for grazing until a mean stocking date of 17 February. Cattle were stocked at the target 1.8 Mg ha^{-1} wheat pasture rate except when the 2006 wheat crop was not established. Cattle grazed wheat forage and sorghum stover (Baumhardt et al., 2009) for approximately 29 d for a total mean gain of 147 kg ha^{-1} that generated grazing income of approximately \$113 ha^{-1} (\$38 ha^{-1} annualized over the 3-yr WSF rotation) based on the typical regional grazing contract rate of \$0.77 kg^{-1} gain. In comparison with wheat marketed using a mean 2009 price of \$150 Mg^{-1}, this income equated to a grain yield of 0.75 Mg ha^{-1} (0.25 Mg ha^{-1} annualized). The grain yield required for an income equivalent to cattle gain represents the tolerance for possible depression of grain yield due to grazing, or in the absence of yield depression, the additional profit.

Soil Water Management

We compared tillage and grazing effects on soil water at planting during the years 2005 through 2009. Annual precipitation averaged 426 mm and ranged from a low of 257 mm in 2009 to a high of 507 mm in 2007 or from 52 to 102% of the 496 mm long-term mean (Baumhardt and Salinas-Garcia, 2006). Lack of precipitation during planting often prevents dryland crop establishment and will limit growth and yield unless stored soil water offsets developing water deficits. Profile soil water content at wheat planting was generally unaffected by grazing and ranged from approximately 125 ± 2 mm in 2007 up to 220 ± 6 mm in 2008 for both grazed and ungrazed plots (Table 1). Soil water content at wheat planting was greater for NT than for SM in 2005 and 2009, but was not significantly different during the other years (Table 1). Critical wheat establishment precipitation during September and October exceeded 150% of the 90 mm long-term mean and negated the soil profile water differences at planting for wheat harvested in 2005 and 2009. In contrast, wheat for harvest in 2006 could not be established because of insufficient early season precipitation totaling only 25.6 mm, even though the 202-mm profile soil water content at planting approached soil capacity.

Similar comparisons of soil water content at sorghum planting were significantly greater for NT compared with SM tillage in 2005, 2006, and 2009, which averaged 23 mm more soil water for NT than with SM tillage for a potential sorghum grain yield increase of 0.25 Mg ha (Unger and Baumhardt, 1999). Although residue has the potential to retain wind blown snow, fallow precipitation as snow ranged from 8 to 60 mm at 3 to 6 mo before planting; therefore, we attributed greater profile soil water storage with NT to reduced evaporation from soil covered with wheat residue in contrast to disturbed SM tilled plots with incorporated residue. No significant differences in soil water at sorghum planting developed between the grazed and ungrazed

Table 1. Annual summary of the mean 1.8-m profile available soil water at planting for wheat and sorghum in response to tillage and grazing treatments with the corresponding ANOVA significance levels. Grazing by tillage means within years followed by the same letter are not significantly different according to the Tukey honestly significant difference test.

Effect†		2005	2006	2007	2008	2009	Mean‡
		Year harvested					
Wheat		Soil water, mm					
Grazing	G	185	203	127	214	132	172
	UG	182	201	124	226	125	172
Tillage	SM	175	198	130	217	118	168
	NT	192	205	121	224	139	176
Grazing × tillage	G-SM	173	197	116a	211	129ab	165
	G-NT	197	208	138a	218	134ab	179
	UG-SM	178	200	144a	223	106b	170
	UG-NT	187	202	105b	230	144a	173
Significance		P > F					
Grazing		0.56	0.92	0.88	0.22	0.78	
Tillage		<0.01	0.20	0.12	0.21	<0.01	
Grazing × tillage		0.09	0.35	<0.01	0.93	0.02	
Sorghum		Soil water, mm					
Grazing	G	224	139	193	89	78	145
	UG	225	155	193	140	116	166
Tillage	SM	217	133	194	100	83	145
	NT	231	160	193	129	111	165
Grazing × tillage	G-SM	216	131	192	72	81b	139
	G-NT	232	147	195	106	75b	151
	UG-SM	219	135	195	128	84b	152
	UG-NT	231	174	190	153	147a	179
Significance		P > F					
Grazing		0.86	0.42	0.95	0.09	0.16	
Tillage		0.01	<0.01	0.85	0.08	0.01	
Grazing × tillage		0.73	0.06	0.48	0.80	<0.01	

† Grazing effects were grazed (G) and ungrazed (UG); Tillage effects were stubble-mulch (SM) and no-tillage (NT).

‡ Means averaged across study years are provided for reader convenience.

Table 2. Annual summary of the mean starting wheat forage and wheat grain yield in response to tillage and grazing treatments with the corresponding ANOVA significance levels. Grazing by tillage means within years followed by the same letter are not significantly different according to the Tukey honestly significant difference test.

Effect†		2005	2006	2007	2008	2009	Mean‡
		Year harvested					
Wheat forage		Forage, Mg ha^{-1}					
Grazing	G	0.22	–	0.64	1.51	0.29	0.67
	UG	0.36	–	0.86	1.65	0.41	0.82
Tillage	SM	0.27	–	0.78	1.54	0.36	0.74
	NT	0.30	–	0.72	1.62	0.34	0.75
Grazing × tillage	G-SM	0.20	–	0.58b	1.52	0.31	0.65
	G-NT	0.24	–	0.70b	1.50	0.28	0.68
	UG-SM	0.37	–	0.74b	1.56	0.41	0.82
	UG-NT	0.35	–	0.98a	1.75	0.40	0.81
Significance		P > F					
Grazing		0.01	–	0.12	0.43	0.01	
Tillage		0.01	–	0.29	0.23	0.02	
Grazing × tillage		0.27	–	<0.01	0.12	0.33	
Wheat yield		Grain, Mg ha^{-1}					
Grazing	G	1.86	–	2.36	0.89	0.79	1.47
	UG	2.57	–	3.01	1.16	0.91	1.91
Tillage	SM	2.02	–	2.93	0.79	0.73	1.62
	NT	2.41	–	2.44	1.26	0.97	1.77
Grazing × tillage	G-SM	1.64	–	2.78	0.89b	0.63	1.48
	G-NT	2.07	–	1.93	0.88b	0.94	1.46
	UG-SM	2.40	–	3.08	0.69b	0.82	1.75
	UG-NT	2.74	–	2.94	1.63a	0.99	2.08
Significance		P > F					
Grazing		0.21	–	0.23	0.19	0.22	
Tillage		0.09	–	0.07	<0.01	<0.01	
Grazing × tillage		0.83	–	0.18	<0.01	0.27	

† Grazing effects were grazed (G) and ungrazed (UG); Tillage effects were stubble-mulch (SM) and no-tillage (NT).

‡ Means averaged across study years are provided for reader convenience.

plots (Table 1). Nevertheless, we identified nonsignificant soil water differences due to grazing effects in 2009 that approximated the soil water differences attributed to significant tillage effects. These grazing treatment-effect interpretations are an artifact of the split plot design analyses that tests the grazing main treatment-effects more rigorously than the nested tillage effects.

Successful dryland cropping systems typically emphasize conservation of precipitation as stored soil water to stabilize crop yield. Our data show that grazing did not significantly decrease soil water content at wheat or sorghum planting except for the 2009 NT plots being planted to sorghum. Compared with SM residue management, storage of precipitation with NT significantly increased soil water at planting in 2005 and 2009 during fallow after sorghum and in 2005, 2006, and 2009 during fallow after wheat. We attributed this to less evaporation with NT because of the combined effect of increased residue cover and no soil disturbance compared with SM tillage practices.

Wheat Growth and Yield

Dryland wheat utilizes precipitation and available soil water for vegetative growth that we report by year in Table 2 as starting forage. During our 5-yr experiment, the annual mean starting forage ranged from 0 Mg ha^{-1} because of failed wheat establishment in 2006 to a maximum of 1.6 Mg ha^{-1} in 2008. The below-average growing season precipitation of 149 mm in 2008 only exceeded the 119 mm in 2006 (Fig. 2.), but the near maximum 221 mm available soil water at wheat planting for 2008 harvest supplemented the 55-mm September-to-October rain to maintain forage growth. Precipitation during 2005, 2007, and 2009 supported fall wheat establishment and in 2009 exceeded the long-term average monthly growing season precipitation until May. Starting forage measured during those remaining years decreased with grazing and resulted in the 5-yr experimental average of 0.67 Mg ha^{-1} for grazed plots compared with 0.81 Mg ha^{-1} for ungrazed plots. Improved seed–soil contact in the untrampled ungrazed plots probably promoted better stand establishment in friable soil and subsequent growth that resulted in the greater starting wheat forage as observed by Baumhardt et al. (2009).

Removal of wheat forage by grazing reduces crop biomass and leaf area, which can force water use for vegetative recovery at the expense of reproductive growth and stable grain yield. Grazing decreased seed head number, an indicator of reproductive growth, significantly to 314 heads m^{-2} from the 490 heads m^{-2} observed in ungrazed plots during 2008 but not in any other year (data not shown). Differences in seed head number

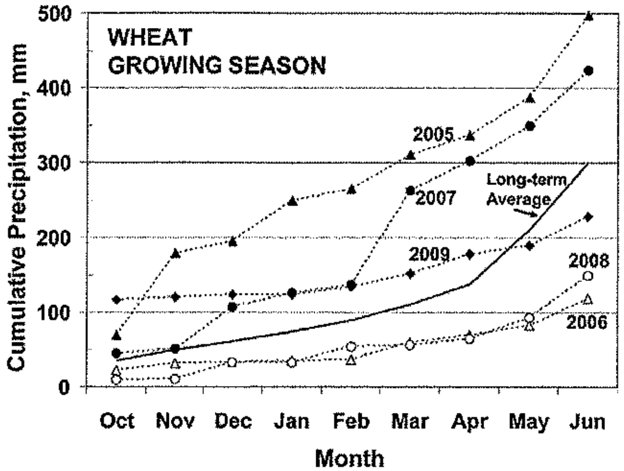

Fig. 2. Cumulative monthly precipitation during the October through June wheat growing season is plotted (dashed lines) by the grain harvest years 2005 through 2009. The long-term average cumulative precipitation is shown as a solid line.

due to tillage effects were either not significant, as observed during 2005 and 2009 or contradictory as shown by the reversal of tillage effects that favored SM in 2007 and NT in 2008. We attributed this reversal in tillage effects to above-average precipitation beginning in March of 2007 (Fig. 2) that could promote vegetative growth in contrast to the below-average 2008 precipitation that promoted greater reliance on soil water and evaporation control with NT residue.

Annual mean wheat grain yields (Table 2) ranged from a crop failure in 2006 with 119 mm precipitation up to highs of 2.21 and 2.68 Mg ha^{-1} for 2005 and 2007 in response to seasonal precipitation of 497 and 424 mm, respectively. The extremes in precipitation for these 3 yr ranged from 40 to 166% of the long-term average, and masked any effect of the tillage or grazing treatments. Likewise, the measured mean seed mass did not vary with tillage or grazing treatments during years with above-average precipitation (data not shown). Wheat grain yields in 2008 and 2009, with below-average seasonal precipitation of 149 to 229 mm (50 to 76% of long-term average), were unaffected by grazing treatment but significantly greater for NT than with SM tillage (Table 2). This tillage effect on wheat yield interacted with grazing treatment in 2008 and was manifested only in the ungrazed plots that ranged from 0.69 Mg ha^{-1} for SM to 1.63 Mg ha^{-1} for NT. Grazing neutralized tillage effects on wheat grain yield during this dry year. The corresponding mean seed mass of 26.1 mg kernel^{-1} for NT was significantly greater than 25.2 mg kernel^{-1} for SM in 2008, but was unaffected in 2009 by the tillage or grazing treatments. Because wheat grain yields during the study did not vary significantly with grazing, the potential value of cattle gain adds to cropping system productivity.

Water use by wheat (i.e., seasonal precipitation plus the soil water difference between planting and harvest) averaged across all treatments ranged from a low of ~280 mm in 2009 up to a high of ~530 mm in 2007 and reflected the importance of both precipitation total and distribution (Table 3). For example, above-average October precipitation for the 2009 wheat crop (Fig. 2) did not increase water use in contrast to the 2007 wheat when rain during the more demanding reproductive stage increased water use. Water use by wheat in 2005 increased

Table 3. Annual summary of the mean water use and water use efficiency (WUE) by wheat in response to tillage and grazing treatments with the corresponding ANOVA significance levels. Grazing by tillage means within years followed by the same letter are not significantly different according to the Tukey honestly significant difference test.

Effect†		Year harvested					
		2005	2006	2007	2008	2009	Mean‡
Water use		mm					
Grazing	G	367	–	531	354	294	387
	UG	340	–	525	368	272	376
Tillage	SM	352	–	538	359	285	383
	NT	356	–	519	362	281	379
Grazing × tillage	G- SM	350ab	–	524ab	350	297	380
	G-NT	384a	–	539ab	358	290	393
	UG-SM	354ab	–	551a	368	272	386
	UG-NT	327b	–	499b	367	272	366
Significance		$P > F$					
Grazing		0.25	–	0.69	0.50	0.27	
Tillage		0.81	–	0.20	0.70	0.76	
Grazing × tillage		0.05	–	0.03	0.65	0.75	
WUE		kg m^{-3}					
Grazing	G	0.51	–	0.45	0.25	0.28	0.37
	UG	0.79	–	0.58	0.31	0.34	0.51
Tillage	SM	0.58	–	0.54	0.22	0.26	0.40
	NT	0.72	–	0.48	0.35	0.36	0.48
Grazing × tillage	G-SM	0.47	–	0.53a	0.25b	0.22	0.37
	G-NT	0.55	–	0.36b	0.25b	0.37	0.37
	UG-SM	0.68	–	0.56a	0.19b	0.30	0.43
	UG-NT	0.90	–	0.59a	0.44a	0.38	0.58
Significance		$P > F$					
Grazing		0.23	–	0.24	0.17	0.21	
Tillage		0.06	–	0.18	<0.01	<0.01	
Grazing × tillage		0.34	–	0.04	<0.01	0.46	

† Grazing effects were grazed (G) and ungrazed (UG); Tillage effects were stubble-mulch (SM) and no-tillage (NT).

‡ Means averaged across study years are provided for reader convenience.

significantly with grazing only in NT plots, which mirrors the soil water status at planting. The grazing × tillage interaction was reversed in 2007 because water use in ungrazed plots was greater for SM than NT. The corresponding calculated WUE did not vary by treatment in 2005, but WUE decreased significantly with NT in grazed plots during 2007. In the absence of grazing, WUE during 2008 benefitted from NT sufficiently to be manifested as a significant tillage main treatment effect. During 2009, NT increased WUE significantly compared with SM tillage probably because the greater stored soil water at planting in NT met crop needs during the drier growing seasons.

Sorghum Growth and Yield

In our grazing system, cattle supplemented growing wheat forage with standing stover from the previous sorghum harvest except for the ungrazed 2006 season. During the remaining years, mean annual starting sorghum stover reflected no significant tillage or grazing effects with an overall mean of 4.25 Mg ha^{-1} for the 5-yr study (data not shown). Annual stover amounts averaged across the combined treatments ranged from a low of 2.6 Mg ha^{-1} for 2007 up to a maximum of 5.88 Mg ha^{-1} for 2008. This highest observed stover yield corresponds to the lowest overall mean grain yield of 2.28 Mg ha^{-1} in 2008 because vigorously growing

Table 4. Annual summary of the mean sorghum seed mass and grain yield in response to tillage and grazing treatments with the corresponding ANOVA significance levels. Grazing by tillage means within years followed by the same letter are not significantly different according to the Tukey honestly significant difference test.

Effect†		Year harvested 2005	2006	2007	2008	2009	Mean‡
Sorghum seed mass		Kernel, mg					
Grazing	G	28.7	16.7	18.1	28.6	24.1	23.3
	UG	29.1	15.7	18.0	28.3	24.9	23.2
Tillage	SM	25.9	16.5	18.8	27.4	25.2	22.8
	NT	31.9	15.8	17.4	29.5	23.8	23.7
Grazing × tillage	G- SM	25.7	17.3	18.8	27.7	25.8a	23.1
	G-NT	31.8	16.1	17.5	29.5	22.4b	23.4
	UG-SM	26.0	15.8	18.7	27.1	24.6ab	22.4
	UG-NT	32.1	15.6	17.3	29.5	25.2ab	23.9
Significance		$P > F$					
Grazing		0.29	0.40	0.82	0.66	0.57	
Tillage		<0.01	0.12	<0.01	<0.01	0.06	
Grazing × tillage		>0.99	0.25	0.97	0.66	0.01	
Sorghum yield		Grain, Mg ha^{-1}					
Grazing	G	4.33	3.49	4.25	1.96	1.48	3.10
	UG	4.23	3.83	4.13	2.59	3.44	3.65
Tillage	SM	4.18	3.56	4.07	1.94	1.88	3.13
	NT	4.38	3.76	4.30	2.61	3.04	3.62
Grazing × tillage	G- SM	4.19	3.48	4.15	1.97b	1.63b	3.08
	G-NT	4.48	3.50	4.34	1.95b	1.33b	3.12
	UG-SM	4.18	3.65	3.99	1.91b	2.14b	3.17
	UG-NT	4.28	4.02	4.26	3.27a	4.75a	4.12
Significance		$P > F$					
Grazing		0.89	0.48	0.81	0.20	0.03	
Tillage		0.53	0.47	0.34	0.03	<0.01	
Grazing ′ tillage		0.77	0.52	0.87	0.03	<0.01	

† Grazing effects were grazed (G) and ungrazed (UG); Tillage effects were stubble-mulch (SM) and no-tillage (NT).

‡ Means averaged across study years are provided for reader convenience.

sorghum plants depleted the soil water before grain was produced. Stover varies independently of the grain yield because soil water at planting and precipitation timing during the growing season can promote either vegetative or reproductive growth.

Sorghum seed heads and, consequently, number of seed can indicate plant stress during the early growing season, while seed mass will vary with late season stress (Krieg and Lascano, 1990). We compared seed head number to indirectly assess early season stress of sorghum; that is, seed heads in excess of the 8 plants m^{-2} target population indicate favorable growing conditions that promoted development of fertile tillers. Seed head number did not vary significantly with either tillage or grazing treatments during the years 2005 through 2008 with annual averages ranging from ~10 to 11.5 heads m^{-2} (data not shown). Because of an interaction between grazing and tillage treatments, seed head number in 2009 did not vary significantly by grazing treatment in SM plots; however, compared with the 9.6 heads m^{-2} in SM plots, seed head number increased to 12.3 heads m^{-2} in ungrazed-NT plots or decreased ~40% in grazed-NT plots. These data illustrate the effects of both favorable early growing season conditions in ungrazed-NT plots and the benefit of SM tillage disturbance to counteract compaction due to trampling for improved early season growth compared with grazed-NT plots.

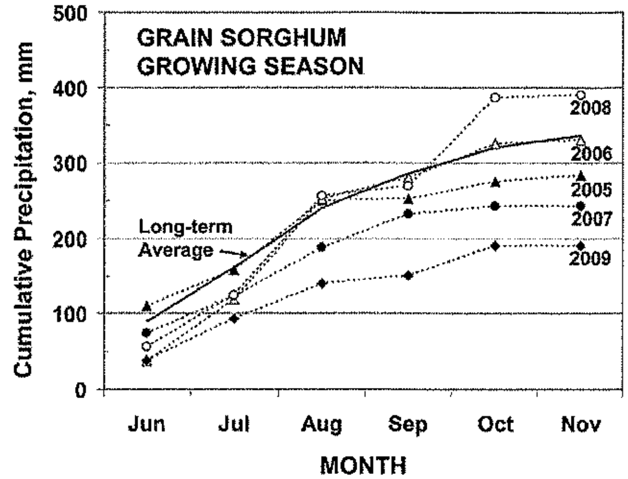

Fig. 3. Cumulative monthly precipitation during the June through November sorghum growing season is plotted (dashed lines) for the years 2005 through 2009. The long-term average cumulative precipitation is shown as a solid line.

Annual sorghum grain yields averaged across both tillage and grazing treatments (Table 4) were <2.5 Mg ha^{-1} in 2008 and 2009 because the soil water at planting of <115 mm was not sufficient to offset crop water stress due to below-average precipitation during June and July in 2008 and the entire growing season in 2009 (Fig. 3). The greatest pooled mean annual yield of 4.28 Mg ha^{-1} in 2005 occurred because the corresponding pooled mean soil water at planting of 224 mm was available to augment typical growing season precipitation of 158 mm. Sorghum grain yield did not vary significantly in response to the tillage or grazing treatments for the high-yield year of 2005 or during the years 2006, and 2007 (Table 4) with favorable annual yield means of 3.66 and 4.18 Mg ha^{-1}. During 2008 and 2009 a significant grazing × tillage interaction was identified because sorghum grain yields for NT exceeded those for the corresponding SM tillage in ungrazed plots, but tillage effects were masked in grazed plots. A significantly greater seed mass during 2005 and 2008 (Table 4) reflected favorable NT effects to reduce evaporation and improve soil water availability later in the growing season. However, NT effects to increase seed mass compared with SM were reversed in 2007. During 2009, a significant tillage × grazing interaction was manifested by increased seed mass for SM tillage compared with NT only in grazed plots. Grazing affected sorghum grain yield independently during 2009 by decreasing grain yield from 3.44 Mg ha^{-1} in ungrazed plots to 1.48 Mg ha^{-1} in grazed plots. We identified a significant tillage × grazing interaction that shows grazing depressed the 2008 and 2009 mean grain yield in NT plots but not in SM plots probably because SM tillage eliminates soil surface compaction due to trampling.

Annual sorghum water use (Table 5) averaged approximately 350 mm during 2005, 2006, and 2007, because precipitation and stored soil water were favorable, but decreased to ~240 mm in 2008 and 215 mm in 2009 due to limited soil water and precipitation (Fig. 3). Sorghum water use did not vary in response to tillage or grazing treatments during 2005, 2007, and 2009; however, observed water use increased significantly with NT management during 2006 and 2008 that featured average or above-average precipitation (Fig. 3). The corresponding WUE was similarly greater for NT compared with SM tillage in 2009 because NT increased water conservation and, consequently, yield (Table 5). Grazing did not independently affect WUE; however, a significant grazing × tillage interaction during 2008 resulted when the WUE with NT surpassed that of SM for ungrazed plots and resulted in no WUE difference due to tillage in grazed plots. Likewise, a significant grazing by tillage interaction during 2009 was evident as NT increased WUE for ungrazed compared with grazed plots, but unaffected by grazing for SM plots. Our data suggest that grazing negated tillage effects on WUE probably by limiting infiltration of rain, while NT increased WUE compared with SM in ungrazed plots by reducing evaporation that promoted greater water use and yield.

Soil Fertility and Soil Penetrometer Resistance

Cattle-grazing was integrated into the WSF rotation to convert wheat forage and sorghum stover into marketable animal gain at the expense of removing biomass that is normally available for N mineralization. Crop sensitivity to this potential deficiency in plant-available N would be reflected as reduced grain N content. We measured N content for sorghum grain harvested in 2009 to determine if N availability may have limited crop growth and grain yields that ranged from a low of 1.33 Mg ha^{-1} for grazed-NT up to 4.75 Mg ha^{-1} for ungrazed-NT. The measured sorghum grain N averaged ~22 g kg^{-1} across all grazing and tillage combinations; and contrary to expectations, the 18.5 ± 1.9 g kg^{-1} grain N for the highest yielding ungrazed-NT treatment was significantly lower than the 22.9 ± 1.8 g kg^{-1} observed for grazed-NT or 23.1 ± 1.2 g kg^{-1} measured for the SM grazing treatments. Nevertheless, the grain N content for ungrazed-NT sorghum was consistent with the expected 19.6 g kg^{-1} for sorghum (NRCS, 2009). The higher N content observed for the other tillage and grazing treatment combinations suggests N availability was sufficient to meet crop demand and contradicts possible limited N mineralization due to biomass removal by grazing cattle despite any N additions related to manure. Nitrogen use calculated from grain yield and N concentration ranged up to a high of 87.2 kg ha^{-1} for ungrazed NT and appeared to be driven more by yield amount than by N availability. We, therefore, suspected that any observed decrease in grain yield would probably be governed by soil properties such as water content and density.

Soil PR can qualitatively characterize the simultaneous effects of soil compaction and water content on soil strength with a single measurement. The PR measured during the *fallow after sorghum* cropping phase in 2007 approximately 1 mo before planting wheat is plotted with depth to 0.45m for grazed and ungrazed treatments under NT or SM tillage (Fig. 4). Soil water did not vary for either tillage or grazing treatments with depth, averaging 0.335 ± 0.005 m^3 m^{-3} for the 0- to 0.30-m depth and 0.380 ± 0.005 m^3 m^{-3} for the 0.30- to 0.60-m depth. Mean PR did not vary with grazing treatment and averaged significantly more for NT at 1.25 MPa compared with 1.14 MPa for SM tillage. An analysis × depth showed that PR above 0.125 m or the approximate SM tillage plow depth was significantly lower than with the corresponding NT for both grazed and ungrazed treatments because SM tillage disturbance offset normal NT soil consolidation. The gradual PR increase with increasing depth > 0.0125 m may be

Table 5. Annual summary of the mean water use and water use efficiency (WUE) by the subsequent grain sorghum crop in response to tillage and grazing treatments with the corresponding ANOVA significance levels. Grazing by tillage means within years followed by the same letter are not significantly different according to the Tukey honestly significant difference test.

Effect†		Year harvested 2005	2006	2007	2008	2009	Mean‡
Water use		mm					
Grazing	G	354	360	347	222	192	295
	UG	350	364	343	254	237	310
Tillage	SM	349	352	344	222	208	295
	NT	355	372	346	254	221	310
Grazing × tillage	G-SM	345	354	345	200	196	288
	G-NT	363	365	349	244	188	302
	UG-SM	352	349	344	244	220	302
	UG-NT	347	378	342	265	225	317
Significance		P > F					
Grazing		0.81	0.68	0.69	0.16	0.10	
Tillage		0.35	0.02	0.88	0.01	0.39	
Grazing × tillage		0.10	0.32	0.67	0.34	0.17	
WUE		kg m^{-3}					
Grazing	G	1.23	0.98	1.23	0.89	0.82	1.03
	UG	1.21	1.06	1.20	1.01	1.51	1.20
Tillage	SM	1.20	1.02	1.18	0.88	0.97	1.05
	NT	1.24	1.02	1.25	1.02	1.36	1.18
Grazing × tillage	G-SM	1.22	0.99	1.21	0.98ab	0.92b	1.06
	G-NT	1.24	0.97	1.25	0.81ab	0.73b	1.00
	UG-SM	1.18	1.05	1.16	0.79b	1.03b	1.04
	UG-NT	1.24	1.07	1.25	1.23a	1.99a	1.36
Significance		P > F					
Grazing		0.89	0.59	0.84	0.42	0.09	
Tillage		0.65	0.96	0.37	0.24	0.04	
Grazing × tillage		0.86	0.82	0.73	0.01	<0.01	

† Grazing effects were grazed (G) and ungrazed (UG); Tillage effects were stubble-mulch (SM) and no-tillage (NT).

‡ Means averaged across study years are provided for reader convenience.

characteristic of instrument drag. Grazing did not significantly increase PR at any depth for either NT or SM tillage when measured during fallow after sorghum. The diminished grazing effects on PR could be attributed to multiple freeze–thaw and wet–dry cycles during the 2-yr period since grazing wheat that negated possible soil compaction due to cattle trampling.

Grazing and tillage effects on PR were also determined during the *fallow after wheat* rotation phase 1 mo after wheat harvest and within 6 mo of grazing. As observed for the fallow after sorghum, soil water did not vary for either tillage or grazing treatments with depth, but averaged drier contents of 0.257 ± 0.008 m^3 m^{-3} and 0.234 ± 0.008 m^3 m^{-3} for the 0- to 0.30-m and 0.30- to 0.60-m depths, respectively. These more recently grazed plots exhibited a significantly higher overall mean profile PR of 2.25 MPa compared with 1.43 MPa for ungrazed plots. Also for fallow after recently grazed wheat, SM tillage reduced the overall mean profile PR to 1.61 MPa, which was significantly lower than the 2.07 MPa PR for NT soil. A plot of PR with depth in grazed plots (Fig. 5) showed that PR above 0.125 m or the approximate SM tillage plow depth were reduced significantly compared with the consolidated NT treatment. For depths > 0.25 m, the measured PR for grazed NT plots was greater than the PR at corresponding depths in

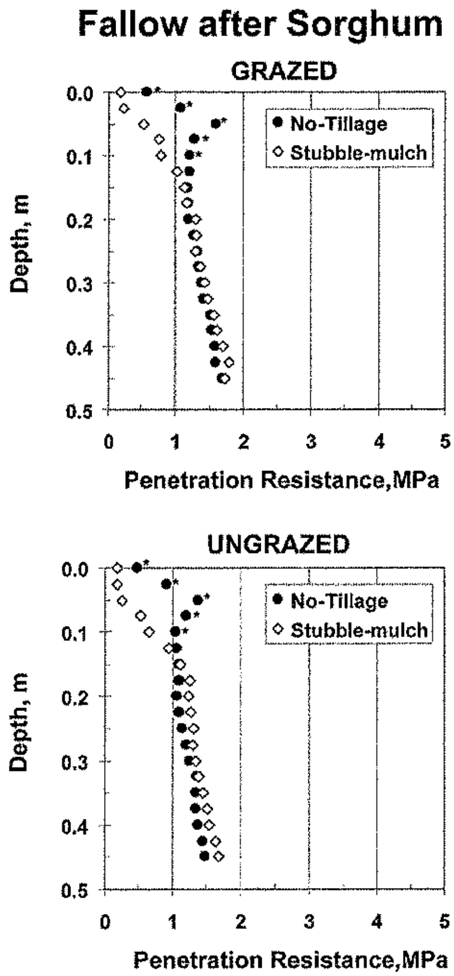

Fig. 4. No-tillage or stubble-mulch tillage effects on penetration resistance (PR) measured with depth in 2007 on grazed and ungrazed plots during the fallow after sorghum rotation phase. For each depth, plotted PR designated by * differed significantly with tillage treatment.

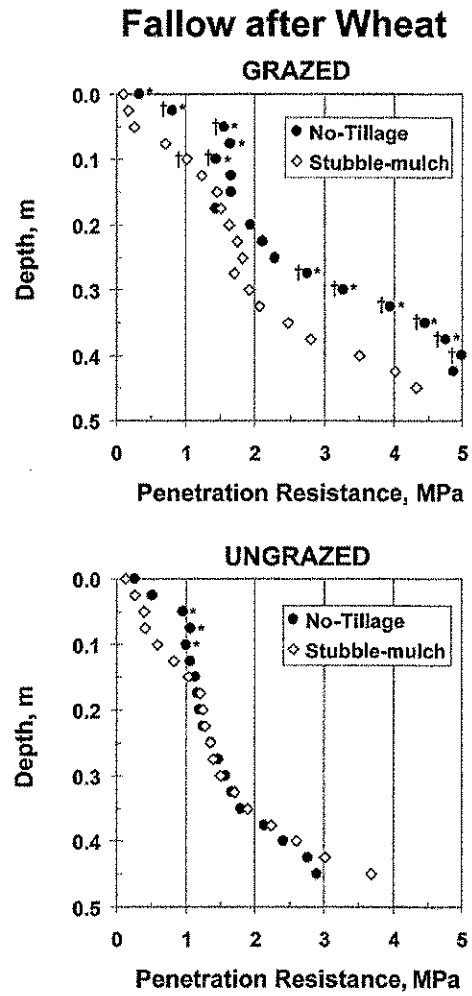

Fig. 5. No-tillage or stubble-mulch tillage effects on penetration resistance measured with depth in 2007 on grazed and ungrazed plots during the post-wheat-harvest idle period. For each depth, plotted PR designated by * or † differed significantly with tillage or grazing treatment, respectively.

SM plots. In contrast, the PR with depth in ungrazed plots (Fig. 5) did not differ significantly between tillage practices below 0.1 m and was not significantly different from PR in grazed plots with SM tillage. Soil surface compaction due to grazing can reduce rain infiltration and variable soil water content, which may have contributed to increased PR at depths > 0.25 m for grazed NT plots compared with the corresponding grazed SM plots or the PR for both ungrazed NT or SM plots. These data illustrate benefits of SM tillage to offset soil compaction caused by grazing that increased PR.

SUMMARY AND CONCLUSIONS

Although limited, grazing of dryland wheat forage and sorghum stover successfully increased productivity of the WSF cropping system under SM tillage by an amount that was roughly half of the mean wheat yield. The available soil profile water content at planting was typically greater for NT compared with SM tillage, averaging 8 and 20 mm more with NT for wheat and sorghum, respectively. Soil profile water content at sorghum planting did not vary significantly with grazing treatment even though observed differences exceeded the corresponding tillage effects; however, future research using more powerful experimental designs may provide a more rigorous test. A developing cumulative grazing effect in NT plots, possibly due to compaction by trampling that SM remediated, reduced storage of fallow precipitation as soil water and, consequently, depressed grain yield of the NT wheat and sorghum sufficiently to offset much of the grazing benefits. Siri-Prieto et al. (2007, 2009) recommended deep tillage after winter annual grazing for improved water use and yield of subsequent cotton and peanut in the southeastern Piedmont. Similarly, we recommend post-wheat-harvest SM tillage to disrupt soil compaction due to grazing and restore soil productivity.

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