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Integrating sheep grazing into wheat–fallow systems: Crop yield and soil properties☆

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ABSTRACT

The two predominant systems for weed management in summer fallow are tillage with a field cultivator or multiple applications of broad spectrum herbicides with zero tillage. Both systems are based on substantial use of off farm resources. Our objective was to determine if strategic grazing of sheep may allow grain growers to more sustainably manage crop residues, volunteer crop, and other weeds during fallow periods. We conducted a study near Bozeman, Montana, USA, comparing three fallow weed management systems in two crop rotations from 2005 to 2008. Fallow weed management systems were conventional tillage, chemical-fallow (herbicide application), and sheep grazing. The crop rotations were summer fallow–spring wheat and summer fallow–winter wheat. In late fall, chemical-fallow treatment had greater residue cover and soil water content than did tilled- or grazed-fallow. At 0–15-cm depth, soil had lower bulk density in chemical- and tilled-fallow than in grazed fallow. Similarly, soil NO_3-N, Ca, SO_4-S concentrations and EC were lower following grazed-fallow than tilled-fallow, but Na concentration was higher following grazed-fallow than tilled- or chemical-fallow. Following spring and winter wheat, soil properties were not influenced by treatments. Grain yield was greater in winter wheat than in spring wheat but the trend reversed in protein concentration. Although soil properties varied among treatments, fallow management system had little influence on yield or quality of spring and winter wheat. Sheep grazing during fallow periods had limited impact on subsequent wheat yield and quality, and is a suitable practice for weed and residue management in wheat–fallow systems.

1. Introduction

Montana wheat producers use approximately 4.5 million pounds of herbicide active ingredient annually for weed control on summer fallow (Johnson et al., 1997). This represents the largest quantity of herbicides used in Montana. In the northern Great Plains, approximately 6.3 million ha of farm land (National Agricultural Statistics Service, 2007) are rotated with summer fallow annually where herbicides used for weed control on the majority of acres (Stewart, 1988).

Weeds and/or volunteer cereal crops during fallow periods deplete available soil water and N. Weed growth during fallow can reduce wheat yield in the following year by 509–1525 kg ha^{-1} (Greb, 1981) by using substantial amounts of soil water (Schillinger and Young, 2000). In addition, populations of several critically important weed species commonly found in Great Plains cereal grain production areas, including wild oat (*Avena fatua* L.), kochia [*Bassia scoparia* (L.) A.J. Scott], and Russian thistle (*Salsola kali* L.), are resistant to common inexpensive herbicides (Heap, 2012). Herbicide application for weed management typically is among the highest of all variable costs for dryland cropping systems in the northern Great Plains. Summer fallow, typically comprising about 33% of the arable land devoted to dryland crop production in Montana, totaled nearly 1.3 million hectares in 2000 (National Agricultural Statistics Service, 2007). Average costs of pesticides alone used on fallowed land were \$15.01 and \$22.95 ha^{-1} for minimum tillage and chemical fallow, respectively (Johnson et al., 1997).

Currently, conventional tillage is the only alternative to chemical fallow for weed control in summer fallow. However, tillage can incorporate crop residues into the soil, decrease residue cover and organic matter, and increase the potential for soil erosion. Strategic grazing of crop stubble and weeds with sheep (*Ovis aries*) may offer

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an alternative to conventional residue and weed management systems that require high inputs of fossil fuels and pesticides thereby resulting in significant reduction pesticides use and its residues.

Animal feces and urine returned to the soil during grazing can enrich soil nutrients, improve soil quality, and increase crop yields (Franzluebbers and Stuedemann, 2008a; Tracy and Zhang, 2008; Maughan et al., 2009). The distribution of feces and urine by animals during grazing at the soil surface can be uneven; however, distribution can be more uniform with sheep than with cattle (*Bos taurus*) grazing (Abaye et al., 1997). Hatfield et al. (2007b) reported that sheep grazing during fallow to control weeds did not influence soil organic matter and nutrient levels compared with the non-grazed treatment in north central Montana. Abaye et al. (1997) found that sheep grazing increased soil bulk density and extractable P and grass yields compared with cattle grazing. Similarly, Li et al. (2008) reported that soil P and K concentrations were not significantly different between sheep-grazed and non-grazed regions in the desert steppe in Inner Mongolia. Quiroga et al. (2009) reported that 10 yr of cattle grazing did not alter soil P concentration in grazed and non-grazed treatments in Argentina. In contrast, Niu et al. (2009) in Australia observed that soil P and K concentrations were greater in sheep camping than in non-camping sites due to increased animal excreta. Cattle and sheep grazing in pasture can result in similar or increased soil P and K concentrations compared with non-grazing (Mathews et al., 1994; Abaye et al., 1997).

In the U.S. 789 million tons of crop residues are produced annually in excess of that needed to prevent soil erosion (Lechtenberg et al., 1980). In high yielding regions, crop residues are sometimes considered a hindrance for optimum yields. Burning, harvest by baling, or tillage are used to reduce the amount of crop stubble and to control diseases (Dill-Macky and Jones, 2000), insect pests (Farstad, 1944), and weeds (Widtsoe, 1913). Sheep can graze stubble to desired levels, converting it into food and fiber for human consumption (Hatfield et al., 1999; Landau et al., 2000) while reducing feed and environmental costs associated with residue removal (Sharma et al., 2010). Mutual benefits of sheep herbivory for weed control (Walker et al., 1992; Hatfield et al., 2007c) as well as insect pest reduction (Goosey et al., 2002; Hatfield et al., 2007a), residue management, and nutrient cycling (Ryan et al., 2008a,b) were well documented.

Marten and Andersen (1975) documented that several broadleaf and grassy weed species had high forage quality and were as palatable as oats (*Avena sativa* L.) to sheep. Similarly, perennial weed species can have high forage quality and palatability, particularly at vegetative growth stage (Marten et al., 1987). Primary weed species found in summer-fallow in Montana and the northern Great Plains include volunteer cereals, kochia, Russian thistle, wild oats, and cheat grass (*Bromus tectorum* L.), which can be highly palatable to grazing ruminants when plants are in the vegetative stage. Rotational grazing systems have been documented to reduce annual weed infestations (Stone et al., 2006). However, grazing ruminants can negatively impact soil structure (Singleton and Addison, 1999), decrease water infiltration rate (Franzluebbers and Stuedemann, 2008b) and content (Taddese et al., 2002a,b) and increase runoff (Mwendera et al., 1997). Soil compaction can decrease capture and efficiency in radiation and water use by crops (Sadras et al., 2005). Conversely, grazing in cultivated lands can have limited impacts on soil properties in no-tilled, semiarid cropping systems (Quiroga et al., 2009). Although much research has been done on mechanical and chemical management of crop stubble under dryland crops and summer fallow (Wiese, 1983), few results are available on the effects of substituting grazing livestock for chemical or mechanical stubble and associated weed management on annual cropland.

Much is known individually about crop and animal components of agriculture production. However, crop and animal agriculture are less frequently combined for mutually beneficial systems now than in the past. The potential use of crop residues for feed under non-traditional grazing systems that incorporate residue grazing is impressive and not a new concept (National Research Council, 1983). Despite the worldwide application of grazing crop residues (Owen and Kategile, 1984) and the potential for grazing systems that incorporate their use, this subject has received little attention from the research community and US agricultural producers. Conventional agricultural production systems based on chemical inputs have increased crop yields and supplied foods for feeding the world's growing population. However, this may not be the preferred strategy for the future due to economic and environmental factors (Poincelot, 1986; Papendick et al., 1987; Glendining et al., 2009). Integrated, low input systems optimize output per unit of input rather than maximize output at all cost (Stinner and House, 1989).

The overall goal of our study was to compare the impacts of three fallow management and two crop rotation systems on weed control, soil water and nutrient concentration, and grain production. In this study, we evaluated strategically managed sheep grazing-fallow with chemical- and conventionally tilled fallow on wheat grain yield and quality, and soil physical and chemical properties in spring wheat–fallow and winter wheat–fallow rotations from 2005 to 2008 in south central Montana.

2. Materials and methods

2.1. Experimental site

The experiment was conducted from 2004 to 2008 at the Fort Ellis Research and Extension Center, Montana State University, Bozeman, MT (45°40′ N, 111°2′ W; altitude 1468 m). Weather was monitored at the site using a HOBO® Pro Series Weatherproof Temperature Logger (Ben Meadows® Company, Janesville, WI), HOBO® Pro Solar Radiation Shield (Ben Meadows® Company, Janesville, WI), BOXCAR® Pro Software (Ben Meadows® Company, Janesville, WI), HOBO® Shuttle (Ben Meadows® Company, Janesville, WI), and HOBO® Datalogging Rain Gauge (Ben Meadows® Company, Janesville, WI).

The experiment was located in an area mapped as Blackmore silt loam (fine-silty, mixed, superactive, frigid, Typic Argiustolls) with 0–4% slope. The soil had 250 g kg^{-1} sand, 500 g kg^{-1} silt, and 250 g kg^{-1} clay. In spring 2004 two composite cores per plot were obtained with hydraulic probe before the initiation of the experiment. Soil organic carbon concentrations at 0–15 cm and 15–30 cm depths were 33.2 and 17.5 g C kg^{-1}. Soil pH at 0–15 cm and 15–30 cm was 6.7 and 6.5, respectively. Soil nutrients and chemical properties of the prior to initiation of the experiment did not vary significantly ($P < 0.05$) among plots prior to treatment imposition. The previous 10-year cropping history was perennial grass pasture containing a mixture of smooth bromegrass (*Bromus inermis* L.), intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey), and Canada bluegrass (*Poa compressa* L.), followed by one season of tilled fallow in 2003. Tillage in 2003 was done by one pass with an offset disk followed by a field cultivator to 15-cm depth for weed control and seedbed preparation.

2.2. Experimental design

The experiment consisted of two annual crop rotations, spring wheat–summer fallow and winter wheat–summer fallow. Each rotation was included in three summer fallow management practices, tilled-fallow (Tillage), no-tilled chemical-fallow (herbicide application) (Chemical), and sheep-grazed fallow (Graze). The

Table 1
Dates for tillage, herbicide applications, and sheep grazing summer fallow in three management systems and sheep grazing days on grazed fallow for two wheat types, 2005–2008.

Year	Fallow management				
	Tillage[a]	Chemical	Grazing		
		Date		Winter wheat (sheep days ha^{-1})	Spring wheat (sheep days ha^{-1})
2005					
	26 April	2 May	5 May	318	155
	9 June	7 June	31 May	158	79
	16 July	6 July	14 June	387	158
			6 July	136	136
			5 Aug	244	301
2006					
	18 May	10 May	8 May	210	143
	5 June	29 May	1 June	316	38
	14 July	29 June	27 June	423	574
	25 July	11 July	19 July	146	0
			24 July	0	191
			26 July	96	0
2007					
	2 May	1 May	1 May	543	215
	4 June	1 June	31 May	555	330
	13 July	29 June	18 June	368	163
		24 July	16 July	115	110
			8 Aug	182	184
2008					
	20 June	29 May	28 May	134	0
	16 July	19 June[b]	16 June	91	129
	18 August	30 June[c]	7 July	239	210
		23 July	8 Aug	117	148

[a] First tillage each year was done with an offset disk. Subsequent tillage was done with a field cultivator at a depth of 15 cm.

[b] Herbicide treatment applied only to fallow in rotation with spring wheat.

[c] Herbicide treatment applied only to fallow in rotation with winter wheat.

experimental design was a randomized complete block in a split-plot arrangement with three replications. Whole plot treatment was fallow management system: Tillage, Chemical, and Graze. Split plots were individual components of the two crop rotations, winter wheat–summer fallow and spring wheat–summer fallow. The split plot size was 15.2 m × 91.4 m. The three replicates were separated by 9.1 m wide tilled alleys. Each component of every rotation × fallow management combination was present in three replications in each year, resulting in a total of 36 plots. Because all 2004 plots followed 2003 summer fallow, we required one season for true initiation of the experiment. As a result, data for 2004 were not included for analysis.

2.3. *Fallow management practices*

Tillage was done as needed to control volunteer wheat and other weeds. Each spring, tillage plots were initially tilled with an offset disk. All subsequent tillage was done with a field cultivator for tilling to a depth of 15 cm with gauge wheels.

The Chemical plots were not tilled during the fallow year. Herbicides were used to manage weeds, including volunteer wheat. Depending on the species of weeds present, either glyphosate (N-[phosphonomethyl] glycine) alone at 3.36 kg a.e. ha^{-1} or in combination with dicamba (dimethyamine salt of 3,6-dichloro-o-anisic acid) at 0.563 kg ha^{-1} in 37.8 l ha^{-1} water was applied. Surfactant (Wilbur-Ellis R-11, San Francisco, California) at 0.292 l ha^{-1} and ammonium sulfate at 3.36 kg ha^{-1} were mixed with all glyphosate during applications. Herbicides were applied with utility vehicle containing a bed-mounted spray system pressurized by a gasoline-powered motor. Boom width was 3.05 m and herbicides were applied at 275 kPa with groundspeed of 8 km h^{-1}.

The boundaries of each Graze plot were permanently fenced with metal T posts and galvanized sheep net while ends were fenced using 1.7-m tall ElectroStop II temporary fence (Premier Sheep Supplies, Ltd., Washington, IA). These fences were electrified using Intellishock 40B energizers (Premier Fence Systems, Washington, IA) powered by deep cycle batteries (Dura-Start, Exide Corp., Reading, PA). Temporary end fences were removed for tillage, fertilization, herbicide application, and harvest. The Graze plots were grazed by a variety of white-faced sheep that were randomly assigned to plots. Sheep were re-randomized for every grazing occurrence within a season. The stocking rates were in accordance with Hatfield et al. (2007a). The stocking rates were in accordance to the available biomass estimated from pre-graze samples. Water was supplied to sheep in 95-l buckets set away from the electric fence and wired to the permanent fence located between the plots. Sheep had *ad libitum* access to water and salt. Post-grazing soil residue cover was determined by line-transect method (Laflen et al., 1981).

Tillage and herbicide applications were done to manage volunteer wheat and other weeds on summer fallow three to four times during the growing season each year (Table 1). Sheep grazing to control volunteer wheat and other weeds was done three to five times each season. Weed management in Tillage and Chemical treatments was required three or four times each year (Table 1). In 2007, Chemical required one more treatment than Tillage. The Graze averaged 1145 sheep days ha^{-1} and 816 sheep days ha^{-1} on summer fallow in rotation with winter wheat and spring wheat, respectively. Weed management with Graze required one or two more applications, occurrences grazing periods than Tillage or Chemical in three of four years. In 2008, Tillage and Chemical for both rotations and Graze on fallow in rotation with spring wheat required three applications for weed management, while Graze on fallow in rotation with winter wheat required four sheep grazing periods (Table 1). Soil physical and chemical parameters, and residue cover, were assessed after weed control measures were completed.

2.4. Crop management

Crop management practices were described in detail by Sainju et al. (2010). Briefly, spring and winter wheat N fertilizer rates were determined by yield goals, which were adjusted to soil residual NO_3-N content to a depth of 60 cm after crop harvest in the fall. Yield goal for spring wheat and winter wheat was 4800 kg ha^{-1}. Each year, soil samples collected in late fall (mid-October) were analyzed for NO_3-N content at the 0–15, 15–30, and 30–60 cm depth, which was deducted from N fertilization rates (250 kg N ha^{-1} for spring wheat and 200 kg N ha^{-1} for winter wheat) used for each crop (Jacobsen et al., 2003). Nitrogen fertilization for spring wheat was done by broadcasting urea (46% N). Fertilizer was incorporated to a depth of 15 cm with a field cultivator prior to planting spring wheat. Winter wheat received broadcast surface application of urea in the spring following planting. Due to high concentrations of soil available P and K, these fertilizers were not applied. Spring wheat 'McNeal' was planted at 90 kg ha^{-1} in late April–early May and winter wheat 'Promontory' was planted at 73 kg ha^{-1} in late September–early October in 30-cm row spacing with a drill equipped with double-disk openers. A tank-mixed application of 0.68 kg ha^{-1} of formulated bromoxynil and MCPA ester (0.91:1) with 437.4 ml ha^{-1} of R-11spreader activator nonionic surfactant (alkylphenol ethoxylate, butyl alchohol, and dimethylpolysiloxane) (Wilbur-Ellis, San Francisco, CA) in 37.8 l ha^{-1} water was used for in-crop weed management.

2.5. Crop and soil data collection

Aboveground crop biomass (stems, leaves, and grains) was determined by clipping 1 m of row prior to grain harvest, oven drying at 60 °C for 3 d, and weighing samples. An additional 1-m row was sampled for reproductive tiller counts. Ten heads per plot were hand-clipped for determination of seed number and seed weight. Tiller height was determined from ten tillers per plot. Grain yields were determined from an area of 1389 m^2 using a combine harvester equipped with a straw chopper-spreader system. Total yield for each plot was determined with a Flexweigh scale (Enduro Systems, Santa Rosa, CA). Except for 2004, wheat biomass residue after grain harvest was returned to the soil. After grain harvest, soil residue cover was determined using the line-transect method (Laflen et al., 1981). Grain N concentration was determined by near infrared spectroscopy; grain protein concentration was calculated by multiplying N concentration × 5.7. Grain test weight was determined with a Grain Analysis Computer (Dickey-john Corp., Minneapolis, MN).

Two soil cores from each plot were collected with a hydraulic probe for gravimetric soil water content determinations. Soil samples were collected to a depth of 60 cm at three intervals of 0–15, 15–30, and 30–60 cm. Samples were composited by depth, weighed, oven dried at 105 °C, and reweighed to determine water content. For NO_3-N analysis, three soil samples were randomly collected per plot from depths as above, air-dried, and shipped to a commercial laboratory (Agvise Laboratories, Northwood, ND). Nitrate-N analyses were done by autoanalyzer for 2005–2007 samples (Agvise Laboratories, Northwood, ND) and by the USDA, ARS personnel at Sidney, MT for 2008 samples. Samples for 0–15 cm depth (2005–2008) were also analyzed for available P (Olsen-P, Frank et al., 1998), K, Ca, Mg, Na, and cation exchange capacity (CEC) (Warncke and Brown, 1998), SO_4-S (Combs et al., 1998), and electrical conductivity (EC) by 1:2 extract with KCl by the same commercial laboratory. Soil bulk density at pre- and post-summer fallow, and post-harvest was determined from three 91 cm^3 samples with a compaction core sampler (AMS, American Falls, ID).

Table 2
Long-term precipitation and l monthly precipitation during the course of the study.

Month	Precipitation (LT[a]) (mm)	Year			
		2005[b]	2006[b]	2007[b]	2008[b]
January	22	7	11	4	8
February	19	7	2	24	7
March	34	22	19	10	13
April	46	42	66	48	54
May	73	37	34	70	71
June	74	42	68	59	73
July	35	17	17	3	18
August	32	31	18	24	14
September	44	23	26	30	9
October	38	47	73	52	8
November	28	30	5	29	24
December	22	17	7	6	15
May–September[c]	258	150	163	186	182
January–December	465	321	345	350	315

[a] LT: long term (1891–2003) for Montana State University, Bozeman, MT, located 5 km SW of experimental site.

[b] Precipitation values at the experimental site located 5 km NE from Montana State University, Bozeman, MT.

[c] Crop growing season precipitation.

2.6. Statistical analysis

Data were analyzed using the PROC MIXED procedure of SAS (Littell et al., 1996). Fallow management was considered as the main plot variable and the fixed effect, cropping phase, was the split-plot variable and another fixed effect, and year as the repeated measure variable. Random variables were replication and replication × fallow management. Arcsine square root transformations were done for soil residue cover (%) data prior to analyses. Means were separated using the least square means test (Littell et al., 1996). Differences among treatments are reported at the 0.05% level of significance.

3. Results

3.1. Precipitation

Long-term mean annual precipitation for the area is 465 mm, 60% of which occurs during the crop growing season (Table 2). During the study, total precipitation ranged from 68% of long-term normal in 2008 to 78% of normal in 2004. Winter precipitation, mostly in the form of snow from November to March, averaged 48% of the 113-yr average. However, the five-year mean precipitation in April was 105% greater than that of the long-term average. Conversely, May and June precipitation were 78% and 84% of the 113-yr average. Mean monthly air temperature ranged from −5.7 °C in January to 18.9 °C in July.

3.2. Summer fallow phase

In the summer fallow period, soil residue cover varied for fallow management and fallow management × year (Table 3). In 2006 and 2008, residue cover was greater following Chemical and Graze than following Tillage (Table 4). Averaged across years, residue cover was greater following Chemical and Graze than following Tillage but not different between wheat types (Table 3).

Treatments varied among years for gravimetric soil water content at various soil depths (Table 3). Water content at 0–15 and 15–30-cm depths, averaged across wheat types, was higher following Chemical than following Graze and Tillage (Table 3). Averaged across fallow management systems, fallow following spring wheat had higher water content at 0–15 cm than fallow following spring

Table 3
Surface residue cover, gravimetric soil water content, and soil bulk density for summer fallow in three management systems with two wheat types in wheat-summer fallow rotations for four years.[a]

Treatment	Residue cover (%)	Gravimetric soil water (%)			Soil bulk density (0–15 cm) ($\mathrm{Mg\ m^{-3}}$)
		0–15 cm	15–30 cm	30–60 cm	
Fallow management					
Chemical	13 a	24.0 a	24.1 a	20.8	1.21 b
Grazed	12 a	20.3 c	19.7 c	18.7	1.28 a
Tillage	8 b	22.8 b	21.9 b	19.5	1.18 b
Wheat type					
Spring wheat	11	21.8 a	21.7	19.4	1.24
Winter wheat	11	22.9 b	22.1	19.9	1.21
Year					
2005	10	23.8 a	22.6 a	20.8 a	1.25 a
2006	12	24.5 a	22.6 a	20.3 a	1.17 b
2007	10	18.8 c	22.5 a	19.7 a	1.26 a
2008	12	22.4 b	19.9 b	17.8 b	1.22 a
Significance			$P > F$		
Fallow management (F)	**	*	*	NS	*
Wheat type (W)	NS	*	NS	NS	NS
W × F	NS	NS	NS	NS	NS
Year (Y)	NS	***	**	***	***
F × Y	***	NS	NS	NS	*
W × Y	NS	NS	NS	NS	NS
W × F × Y	NS	NS	NS	NS	NS

[a] Means within treatment and column followed by the same letter are not significantly different $P < 0.05$.

wheat. Averaged across treatments, water content at 0–60-cm depth was greater in 2005 and 2006 than in 2007 and 2008.

Soil bulk density at 0–15 cm varied among fallow management systems and years, with a significant fallow management × year interaction (Table 3). Bulk density was greater following Graze than following Tillage in 2005 and 2006 (Table 4). Averaged across wheat types, bulk density was greater following Graze than following Chemical and Tillage (Table 3).

Soil residual NO_3-N concentration at various depths varied among fallow management systems and years, with significant interactions for fallow management × year, and wheat type × year interactions at 0–15 cm (Table 5). In 2005 and 2006, Graze had lower NO_3-N concentration at 0–15 cm, averaged across wheat types, than Chemical and Tillage (Table 4). Averaged across fallow management systems, NO_3-N concentration was greater following winter than following spring wheat in 2006 and 2007 (Table 6). Averaged across wheat types and years, NO_3-N concentration at 0–15 and 15–30 cm was greater following Chemical and Tillage than following Graze (Table 5). Averaged across treatments, NO_3-N concentration at various depths varied among years.

Soil nutrients and chemical properties varied among fallow management and years (Table 7). Averaged across treatments, P

Table 4
Interaction of fallow management × year for surface residue cover, soil bulk density, and NO_3-N concentration for summer fallow in three fallow management systems for four years.[a]

Fallow management	2005	2006	2007	2008
Residue cover (%)				
Chemical	11	16 a	11	13 a
Grazed	9	16 a	10	14 a
Tillage	11	5 b	11	9 b
Soil bulk density ($\mathrm{Mg\ m^{-3}}$)				
Chemical	1.23 b	1.18 a	1.22	1.19
Grazed	1.34 a	1.22 a	1.28	1.28
Tillage	1.17 b	1.09 b	1.27	1.20
NO_3-N concentration, 0–15-cm depth ($\mathrm{mg\ kg^{-1}}$)				
Chemical	47 a	41 a	22	33
Grazed	33 b	25 b	19	31
Tillage	49 a	41 a	24	26

[a] Means within parameters and columns followed by the same letter are not significantly different at $P < 0.05$.

Table 5
Soil NO_3-N concentration from three depths for summer fallow for three fallow management systems and two wheat types in wheat–summer fallow rotations for four years.[a]

Treatment	NO_3-N concentration ($\mathrm{mg\ kg^{-1}}$)		
	0–15 cm	15–30 cm	30–60 cm
Fallow management			
Chemical	36 a	17 a	8
Grazed	27 b	11 b	7
Tillage	35 a	15 a	7
Wheat type			
Spring wheat	32	14	8
Winter wheat	33	15	7
Year			
2005	43 a	17 b	9 a
2006	36 b	20 a	8 a
2007	22 c	11 c	9 a
2008	30 c	11 c	5 b
Significance		$P > F$	
Fallow management (F)	*	*	NS
Wheat type (W)	NS	NS	NS
W × F	NS	NS	NS
Year (Y)	***	***	***
F × Y	*	NS	NS
W × Y	*	NS	NS
W × F × Y	NS	NS	NS

[a] Means within treatment and column followed by the same letter are not significantly different $P < 0.05$.

Table 6
Interaction of wheat type × year for soil NO_3-N concentration for summer fallow in three management systems with two wheat types in wheat–summer fallow rotations for four years.[a]

Year	Spring wheat	Winter wheat
NO_3-N concentration, 0–15-cm depth ($\mathrm{mg\ kg^{-1}}$)		
2005	42 a	44 a
2006	31 b	41 a
2007	22 c	22 b
2008	34 ab	26 b

[a] Means within columns followed by the same letter are not significantly different at $P < 0.05$.

Table 7
Soil (0–15-cm depth) nutrient concentrations, CEC, and EC for fallow in three management systems with two wheat types in wheat–summer fallow rotations for four years.[a]

Treatments	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})	S (mg kg^{-1})	CEC (cmol$_c$ kg^{-1})	EC (dS m^{-1})
Fallow management								
Chemical	73	465	3462 b	497	18 b	16 ab	23	0.40 ab
Grazed	55	351	3451 b	524	21 a	14 b	23	0.35 b
Tilled	65	396	3838 a	516	18 b	17 a	25	0.43 a
Variety								
Spring wheat	65	414	3596	525	20	16	23	0.38
Winter wheat	63	395	3571	500	18	16	23	0.41
Year								
2005	78 a	524 a	–	–	–	–	–	0.30 c
2006	54 b	325 c	3378 b	489 b	16 b	16 b	22 b	0.46 a
2007	71 a	346 bc	3927 a	584 a	21 a	23 a	25 a	0.39 b
2008	54 b	421 b	3446 b	465 b	20 a	9 c	22 b	0.42 ab
Significance					$P > F$			
Fallow management (F)	NS	NS	NS	NS	*	NS	NS	*
Wheat type (W)	NS	NS	NS	NS	NS	NS	NS	NS
W × F	NS	NS	NS	NS	NS	NS	NS	NS
Year (Y)	***	***	**	***	**	***	***	***
F × Y	NS	NS	NS	NS	NS	NS	NS	NS
W × Y	NS	NS	NS	NS	NS	NS	NS	NS
W × F × Y	NS	NS	NS	NS	NS	NS	NS	NS

[a] Means within treatments and columns followed by the same letter are not significantly different $P < 0.05$.

and K concentrations at 0–15 cm depth were greater in 2005 than in 2006 and 2008. Averaged across wheat types and years, Ca and SO_4-S concentrations and EC were greater following Tillage than following Graze, but Na concentration was greater following Graze. Averaged across treatments, Ca, Mg, Na, and SO_4-S concentrations and CEC were greater in 2007 than in 2006 and 2008 but EC was greater in 2006 than in 2005 and 2007.

Table 8
Mean fertilizer N application rate for two wheat types in three fallow management systems in wheat–summer fallow rotations over four years.

Fallow management	Fertilizer application rate (kg N ha^{-1}, as urea)	
	Winter wheat	Spring wheat
Chemical	32	75
Grazed	50	122
Tillage	41	63

3.3. Wheat production phase

Averaged over years, mean fertilizer N application rates were greater for spring wheat than winter wheat (Table 8). The fertilizer N requirement was numerically higher in Graze for both wheat types. Wheat type × fallow management means are provided for reader benefit, and a subsequent manuscript will present N use and nitrogen use efficiencies from this study.

Wheat type, year, and wheat type × year interactions were significant for stem height, wheat biomass, spike density, and grain yield, protein concentration, and volumetric weight (Table 9). Fallow management was significant for spike density. The fallow management × year interaction was significant for grain protein concentration. All crop parameters varied for years (Table 9).

Averaged across fallow management systems, winter wheat was taller than spring wheat in all years (Table 10). Grain and crop biomass yields were greater in spring than in winter wheat in 2005 but the trends reversed in 2007. Grain and biomass yielded greater in 2005 for spring wheat in 2005 and in 2007 for winter than in

Table 9
Crop height, biomass, grain yield and quality following cropping in three management systems with two wheat types in wheat–summer fallow rotations for four years.[a]

Treatment	Stem height (cm)	Crop biomass (kg ha^{-1})	Spikes (# m^{-2})	Seed (# spike^{-1})	Seed (mg seed^{-1})	Grain yield (kg ha^{-1})	Grain protein (g kg^{-1})	Grain weight (kg m^{-3})
Fallow management								
Chemical	83	10,324	501 b	40	42	3417	147	749
Grazed	83	11,109	554 ab	39	43	3502	148	745
Tillage	84	11,947	589 a	40	43	3602	148	746
Wheat type								
Spring wheat	78 b	9818 b	491 b	39	42	3010 b	159 a	763 a
Winter wheat	89 a	12,436 a	605 a	41	42	4004 a	137 b	729 b
Year								
2005	89 a	10,795 b	612 a	–	–	2983 c	164 a	698 c
2006	88 a	10,419 b	528 b	50 a	32	3144 c	142 b	762 ab
2007	88 a	12,719 a	528 b	33 c	54	4119 a	139 c	754 b
2008	70 b	10,573 b	589 b	36 b	40	3783 b	146 d	771 a
Significance					$P > F$			
Fallow management (F)	NS	NS	*	NS	NS	NS	NS	NS
Wheat type (W)	***	***	***	NS	NS	***	***	***
W × F	NS	NS	NS	NS	NS	NS	NS	NS
Year (Y)	***	**	*	***	***	***	***	***
F × Y	NS	NS	NS	NS	NS	NS	*	NS
W × Y	***	***	***	NS	NS	***	***	***
W × F × Y	NS	NS	NS	NS	NS	NS	NS	NS

[a] Within column and treatment followed by the same letter are not significantly different at $P < 0.05$.

Table 10
Interaction of wheat type × year for plant height, crop biomass, grain yield, protein, and weight, and postharvest soil water content and NO_3-N for two wheat types for four years.[a]

Year	Spring wheat	Winter wheat
Height (cm)		
2005	87 a	91 b
2006	86 a	90 b
2007	81 b	95 a
2008	61 c	79 c
Crop biomass (kg ha^{-1})		
2005	11,440 a	10,150 c
2006	9893 ab	10,946 bc
2007	8960 b	16,479 a
2008	8977 b	12,170 b
Grain yield (kg ha^{-1})		
2005	3666 a	3000 d
2006	2892 bc	3395 c
2007	2357 c	5881 a
2008	3124 b	4442 b
Grain protein (g kg^{-1})		
2005	162 a	166 a
2006	157 b	127 b
2007	151 c	127 b
2008	164 a	127 b
Grain weight (kg m^{-3})		
2005	759 b	637 c
2006	753 b	772 a
2007	759 b	748 b
2008	784 a	759 ab
Soil water, 0–15 cm (%)		
2005	20.4 a	23.0 a
2006	21.1 a	21.2 b
2007	12.9 c	13.7 c
2008	18.4 b	20.8 b
NO_3-N concentration, 30–60 cm (mg kg^{-1})		
2005	7 a	4 b
2006	3 c	2 b
2007	5 ab	6 a
2008	4 bc	2 b

[a] Means within parameters and columns followed by the same letter are not significantly different at $P < 0.05$.

Table 11
Interaction of fallow management × year for wheat grain protein in three fallow management systems for four years.[a]

Fallow management	2005	2006	2007	2008
Grain protein (g kg^{-1})				
Chemical	164	142	135 c	147
Grazed	166	142	139 b	146
Tillage	162	143	143 a	144

[a] Means within parameters and columns followed by the same letter are not significantly different at $P < 0.05$.

other years. Grain protein concentration was higher in spring wheat than in winter wheat from 2006 to 2008. Grain weight was greater in spring than in winter wheat in 2005 but the trend reversed in 2006. Averaged across wheat types, grain protein concentration was higher in Tillage than in Graze and Chemical in 2007 (Table 11). Averaged across fallow management and years, stem height, crop biomass, spike number, and grain yield were greater in winter than in spring wheat but grain protein concentration and weight was higher in spring than in winter wheat (Table 9). Averaged across treatments, crop parameters varied among years.

Residue cover, soil water content at various depths, and bulk density varied among years (Table 12). Soil water content at 0–15 cm also differed for wheat type, with a significant wheat × fallow management interaction (Table 12). Soil water content at 0–15 cm was greater in winter than in spring wheat in 2005 and 2008 (Table 10). Averaged across treatments, residue cover was greater in 2008 than in other years but bulk density was greater in 2006 and 2007 than in 2008 (Table 12). Soil water content at various depths varied among years.

Soil NO_3-N concentration at various depths varied among years, with a significant interaction for wheat type × year at 15–30 cm (Table 13). Averaged across fallow management, NO_3-N concentration was greater in spring than in winter wheat in 2005 (Table 10). Averaged across treatments, NO_3-N concentration at 0–15 cm was greater in 2005 than in other years (Table 13). At 15–30 and 30–60 cm, NO_3-N concentration was greater in 2005 and 2007 than in other years.

Soil nutrient concentrations and chemical properties varied with years (Table 14). Soil P and K concentrations were greater in 2005 than in 2006 and 2008. Similarly, soil Ca, Mg, and SO_4-S concentrations were greater in 2007 than in 2006 and 2008 but Na concentration and EC were greater in 2008. The CEC was greater in 2007 and 2008 than in 2006.

Table 12
Soil surface residue cover, gravimetric water, and bulk density following wheat harvest in three fallow management systems for two wheat types in wheat–summer fallow rotations for four years.[a]

Treatment	Residue cover (%)	Gravimetric soil water (%)			Soil bulk density (0–15 cm) (Mg m^{-3})
		0–15 cm	15–30 cm	30–60 cm	
Fallow management					
Chemical	84	18.8	12.7	10.8	1.21
Grazed	83	19.1	13.5	11.1	1.22
Tillage	83	18.9	13.5	11.1	1.22
Wheat type					
Spring wheat	83	18.2 b	13.5	11.0	1.22
Winter wheat	84	19.7 a	13.1	11.0	1.21
Year					
2005	84 b	21.7 a	12.8 bc	11.6 b	1.20 ab
2006	79 c	21.2 a	13.7 ab	12.9 a	1.24 a
2007	83 b	13.3 c	14.8 a	10.6 b	1.24 a
2008	87 a	19.6 b	11.7 c	8.8 c	1.19 b
Significance			$P > F$		
Fallow management (F)	NS	NS	NS	NS	NS
Wheat type (W)	NS	**	NS	NS	NS
W × F	NS	*	NS	NS	NS
Year (Y)	**	***	***	***	*
F × Y	NS	NS	NS	NS	NS
W × Y	NS	NS	NS	NS	NS
W × F × Y	NS	NS	NS	NS	NS

[a] Means within treatment and column followed by the same letter are not significantly different $P < 0.05$.

Table 13
Soil NO_3-N concentration from three soil depths following wheat harvest in three managements systems in wheat–summer fallow rotations for four years.[a]

Treatment	NO_3-N concentration (mg kg^{-1})		
	0–15 cm	15–30 cm	30–60 cm
Fallow management			
Chemical	18	5	4
Grazed	16	4	3
Tillage	15	5	4
Wheat type			
Spring wheat	16	5	5 a
Winter wheat	17	5	3 b
Year			
2005	26 a	6 a	6 a
2006	13 bc	3 b	2 b
2007	11 c	7 a	7 a
2008	16 b	4 b	2 b
Significance		$P > F$	
Fallow management (F)	NS	NS	NS
Wheat type (W)	NS	NS	NS
W × F	NS	NS	NS
Year (Y)	***	***	***
F × Y	NS	NS	NS
W × Y	NS	NS	*
W × F × Y	NS	NS	NS

[a] Means within treatment and column followed by the same letter are not significantly different $P > 0.05$.

4. Discussion

Precipitation deviations from long-term average for the growing season were not substantial over the course of this study, and environmental conditions were suitable for good growth of wheat crops and weeds, including volunteer wheat. Sheep grazing days were substantial, providing robust comparisons among fallow management systems.

4.1. Summer fallow phase

The lower residue cover in Tillage than in Chemical and Graze treatments, especially in 2006 and 2008, was probably due to incorporation of residue due to tillage (Tables 3 and 4). The fact that tillage reduced residue cover especially in 2006 and 2008 could be related with amount of cover crop biomass residue returned to the soil. Crop biomass was lower in 2006 and 2008 than in other years (Table 9). It could be possible that tillage incorporated greater proportion of biomass residue into the soil, thereby leaving lower surface residue cover in Tillage treatment in 2006 and 2008. Residue cover following summer fallow in our study was low regardless of management system. Future studies should strive for greater residue cover following summer fallow regardless of management system for improved protection of soil from wind and water erosion.

In Texas, USA, Baumhardt et al. (2011) compared soil water after fallow, and crop yield in tilled and no-tilled systems with and without grazing by cattle. They reported cattle grazing on sorghum stubble and winter wheat forage increased soil bulk density, but soil water content at crop planting was not affected by grazing. This contrasted with our results, where we found greater soil water content in the surface layers in Chemical-fallow than in Tilled- or Grazed-fallow. Since Chemical-fallow plots were not tilled and herbicides were applied to control weeds, it could be possible that greater water content in this treatment was probably a result of increased residue cover and reduced water removal by weeds. In contract, lower water content in the grazed treatment could be a result of lower surface residue due to its consumption by sheep during grazing. It would not be surprising to observe greater bulk density in Graze compared to Chemical and Tillage since grazing can increase soil compaction and therefore bulk density. Baumhardt and co-workers (2011) recommended stubble-mulch tillage to disrupt soil compaction following grazing. In our study, the small differences in bulk density present soon after termination of sheep grazing fallow were not present following the subsequent wheat crop. The apparent alleviation of bulk density following grazing could be due to freeze–thaw cycles (Unger, 1991) or the pre-plant tillage done for seed bed preparation. Differences in environment are likely the cause of this disparity. Montana USA always has multiple soil freeze–thaw cycles in spring and fall whereas Texas, being nearly 1500 km south, has relatively fewer freeze–thaw cycles.

Our study utilized sheep grazing, and results may not be similar to grazing fallow by other livestock, including cattle, in part because of how different species harvest forage (cattle with their tongue and sheep with prehensile lips). In addition, although both sheep and cattle are Artiodactyla (even-toed ungulates), there is a potential for a difference between species in how hoof action could potential impact soil physical characteristics. Grazing preferences of cattle and sheep can differ (Cowlishaw and Alder, 1960), but vegetative

Table 14
Soil (0–15 cm depth) nutrient concentrations, CEC, and EC following wheat harvest from three fallow management systems in wheat–summer fallow rotations for four years.[a]

Treatments	P (mg g^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})	S (mg kg^{-1})	CEC (cmol$_c$ kg^{-1})	EC (dS m^{-1})
Fallow management								
Chemical	70	414	3506	512	17	14	23	0.29
Grazed	59	400	3319	533	19	12	22	0.28
Tilled	66	383	3536	500	17	16	23	0.30
Variety								
Spring wheat	67	411	3434	515	18	14	23	0.29
Winter wheat	63	387	3473	516	18	15	23	0.29
Year								
2005	76 a	514 a	–	–	–	–	–	0.23 b
2006	60 b	340 c	3165 b	494 b	15 c	16 b	21 b	0.32 a
2007	67 ab	312 c	3673 a	553 a	18 b	19 a	24 a	0.28 ab
2008	58 b	430 b	3522 a	499 b	19 a	8 c	23 a	0.33 a
Significance					$P > F$			
Fallow Management (F)	NS	NS	NS	NS	NS	NS	NS	NS
Variety (V)	NS	NS	NS	NS	NS	NS	NS	NS
V × F	NS	NS	NS	NS	NS	NS	NS	NS
Year (Y)	*	***	**	***	***	***	***	***
F × Y	NS	NS	NS	NS	NS	NS	NS	NS
V × Y	NS	NS	NS	NS	NS	NS	NS	NS
V × F × Y	NS	NS	NS	NS	NS	NS	NS	NS

[a] Means within treatments and columns followed by the same letter are not significantly different $P < 0.05$.

stage, volunteer spring and winter wheat should be highly palatable to both species across a wide range of physiological states, previous grazing histories, and environments. Cattle grazing was shown to have greater impact on bulk density, surface roughness, and net soil disturbance than sheep grazing on wet soils under permanent grass pasture (Betteridge et al., 1999). Regardless of the influence of grazing species, increased bulk density within a soil type often decreases water infiltration rate and soil water holding capacity. In semi-arid environments, reduced water availability and subsequent water use will ultimately cause reduced crop yield (Lenssen et al., 2007, 2012).

Since wheat yields and grain protein concentration was not influenced by fallow management practices, it is likely that reduced soil NO_3-N concentration in grazed-fallow than in chemical or tilled-fallow in 2005 and 2006 (Tables 4 and 5) was due to reduced amount of residue returned to the soil due to its consumption by sheep during grazing. Although N fertilization rates to spring and winter wheat were slightly greater for the grazed treatment (Table 8) and part of N in residue consumed by sheep during grazing can be returned to the soil through feces and urine, it could be possible that N inputs through N fertilizer and sheep feces and urine is lower than N output through residue consumption by sheep. As a result, sheep grazing probably reduced soil NO_3-N concentration in the grazed treatment. Lower NO_3-N concentration in 2007 and 2008 than in 2005 and 2006 was either due to greater wheat grain yield (Table 9) that increased crop N uptake or to increased N leaching due to higher rainfall during summer fallow (182–186 mm from May to September in 2007 and 2008 compared to 150–163 mm in 2005 and 2006) (Table 1).

The lower concentrations of Ca and SO_4-S and EC in the grazed-fallow than in tilled-fallow was probably due to reduced residue returned to the soil due to consumption by sheep during grazing. Since nutrients are recycled as a residue returned to the soil, it could be possible that consumption of residue by sheep reduced its amount in the soil, thereby resulting Ca and SO_4-S levels. Return of nutrient inputs through crop residue can increase soil nutrient levels (Schomberg and Jones, 1999). In contrast, incorporation of residue into the soil may have increased these nutrient levels in tilled-fallow treatment due to rapid mineralization. The higher Na concentration in the grazed-fallow could be a result of greater level of this nutrient through feces and urines. Since sheep were fed with supplemental diet rich in Na (*e.g.*, salt), it could be possible that sheep feces and urine contain higher Na concentration. Since crop biomass was higher in 2007 (Table 9), increase in soil P, Ca, Mg, Na, SO_4-S, CEC, and EC in 2007 than in other years could also be result of greater residue returned to the soil. The higher Na concentration found under sheep grazed fallow may be of critical long term importance if precipitation is insufficient to leach Na below crop rooting zone, an uncommon occurrence in most semi-arid regions. Soil sodicization can greatly decrease yield of wheat (Holloway and Alston, 1992).

4.2. *Wheat phase*

Differences in grain and biomass yields between spring and winter wheat appeared to be related more with growing season precipitation and soil NO_3-N level than crop parameters, such as plant height, spike number, and grain weight. During the dry period with growing season precipitation (May to September) of 150 mm in 2005 (Table 2), spring wheat yielded better than winter wheat (Table 10). In contrast, in 2008 with a growing season precipitation of 182 mm, winter wheat yielded better than spring wheat. Similarly, soil NO_3-N concentration at 30–60 cm was greater under spring than under winter wheat in 2005 but the trend reversed in 2008. This emphasizes that available soil water and N are two most limiting factors of wheat production in dryland cropping systems (Aase and Pikul, 1995; Lenssen et al., 2007; Sainju et al., 2009a,b). In contrast, differences in trends in grain protein content among years suggest that N uptake by wheat probably vary by wheat types or species. Regardless of treatments, both spring and winter wheat yielded better in 2007 when growing season precipitation was higher (186 mm) than in other years but protein concentration was lower. Increased grain yields likely diluted protein concentration in grain (Ryan et al., 2008a). Although number of wheat spikes differed, non-significant difference in wheat grain and biomass yields, grain protein concentration, and other plant characteristics among fallow management systems suggest that sheep grazing can be successfully used to control weeds during fallow periods without influencing wheat yields. This was also supported by the fact that soil water content, NO_3-N concentration, and other soil properties following wheat harvest did not differ among fallow management systems (Tables 12–14).

Although postharvest soil water content at the surface layer was slightly greater under winter wheat than under spring wheat, similar levels of nutrients and chemical properties suggests that both spring and winter wheat are equally competitive in water and nutrient uptake and nutrient cycling by returning part of them through crop residue returned to the soil. This probably resulted in similar residue cover, bulk density, EC, and CEC levels. Variations in residue cover and soil properties among years, however, suggests that these parameters were probably influenced by differences in crop growth, nutrient uptake, and nutrients returned to the soil through crop residue as a result of differences in air temperature and precipitation. In a four-year study, Landau et al. (2007) compared sheep grazing, mulching, and baling of wheat straw in a no-till system and found no differences in wheat yield or yield components, similar to results for wheat yield in the present study. Additionally, Baumhardt et al. (2011) reported that wheat forage or grain sorghum yields seldom were reduced by cattle grazing stubble.

Wheat following sheep grazing required greater nitrogen fertilizer application than other treatments due to lower residual soil nitrate prior to planting. This was likely due to biomass of volunteer wheat and other weeds accumulating substantial nitrogen, an important potential beneficial environmental effect from sheep grazing. Nitrogen concentration of sheep feces may vary depending upon solubility of dietary protein and sheep feces decomposition rate varies with pasture vegetation type (Williams and Warren, 2004); the interactions of diet and vegetation type on nutrient availability to a subsequent wheat crop are not known. Additionally, rates at which N from volunteer wheat or other weeds becomes available for plant uptake are unknown. Cool, semi-arid environments similar to our research site likely have slowly N turnover rates than warmer, wetter environments (Andersen and Jensen, 2001).

Small ruminants grazing crop stubble is a long-term practice in West Asia and North Africa (Landau et al., 2000), but is rarely practiced in North America. An important consideration for implementation of stubble grazing into highly mechanized, extensive North American wheat production systems is that dryland grain farmers are not required to become pastoralists. Rather, collaboration between sheep and grain producers could provide the mutual benefits of reduced costs for feed and summer fallow management, and cultural controls of weeds, insect pests, and crop stubble.

5. Conclusions

Variations in the duration of fallow periods in spring wheat–fallow and winter wheat–fallow rotations resulted in differences in soil physical and chemical properties during fallow, probably due to differences in mineralization of crop residue and soil organic matter, evaporation, and soil compaction levels. Levels of soil properties were, however, similar following wheat harvest, suggesting that both spring and winter wheat probably behaved similarly in water and nutrient uptake, nutrient cycling, residue returned to the soil, and soil compaction. Differences in growth characteristics among wheat types, however, resulted in greater grain and biomass yields but lower grain protein concentration in winter than in spring wheat. Variations in grain and biomass among years were also influenced by differences in soil water content and NO_3-N concentration. Although soil properties varied during fallow periods, non-significant differences in crop yields and characteristics among fallow management systems suggests that sheep grazing during summer fallow is an acceptable method for weed and residue management in wheat–fallow systems without influencing wheat yields in semiarid environments.

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