# Integrating Sheep Grazing into Cereal-Based Crop Rotations: Spring Wheat Yields and Weed Communities

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## ABSTRACT

**Crop diversification and integration of livestock into cropping systems may improve the economic and environmental sustainability of agricultural systems. However, few studies have examined the integration of these practices in the semiarid areas of the Northern Great Plains (NGP). A 3-yr experiment was conducted near Bozeman, MT, to compare the effects of crop rotation diversity and weed management practices imposed during fallow periods [sheep (*Ovis aries*) grazing, reduced tillage, and conventional tillage] on spring wheat (*Triticum aestivum* L.) yields and weed pressure. Management treatments were applied to replicated whole plots, within which the split-plots received crop rotation treatments [continuous spring wheat (CSW) and a 3-yr rotation of annual forage, fallow, and spring wheat, where each phase was present in each year]. In the initial 2 yr, the realized rotational treatments were wheat–fallow and CSW. In the final year, wheat was grown following all phases of the diversified rotation. Yields were similar among management treatments within the wheat–fallow and CSW rotations. Weed pressure was generally low but perennial weeds were more abundant in grazing-managed, wheat–fallow systems. The integration of livestock into the annual hay crop–fallow–spring wheat rotation was associated with a nearly 30-fold increase in weed pressure and a yield reduction of 51.2% compared to conventional management. The results suggest that although targeted sheep grazing is a viable alternative to conventional fallow management in CSW and wheat–fallow rotations, successful integration of livestock in diversified cropping systems requires more effective weed management practices.**

The last century has seen an erosion of diversity in on-farm agricultural systems. Since the 1940s, crop diversity has generally declined in North America (Brummer, 1998). Over the same period, agricultural production shifted from on-farm crop and livestock integration to increasingly spatially separated and specialized operations (Russelle et al., 2007). The evidence is growing that these specialized low-diversity production systems do not produce optimal outcomes for the long-term profitability and sustainability of agriculture and the environment (NRC, 2010).

Restoration of diversity in agricultural production systems through reintegrating livestock into diversified crop production systems has been postulated as an ecologically based approach to reduce off-farm inputs, alleviate negative side-effects of the agricultural enterprise, and increase the efficiency and profitability on the farm (NRC, 2010). To date, research has been conducted in diversified crop–livestock systems where the same field is used for crop and animal production at different times resulting in services being exchanged between livestock and crop components of the production system. In this scenario, grazers provide nutrient-rich manures and urine, improving soil quality and yields (Oltjen and Beckett, 1996; Maughan et al., 2009). Grazing has the potential of also increasing enterprise-level profitability through added value of animal production and reduced feed costs (Karn et al., 2005; Franzluebbers and Stuedemann, 2007; Tracy and Zhang, 2008). However, these previous studies are mostly limited to relatively warm and wet environments where cattle graze on winter-grown cover crops planted into crop residues.

Research is needed to adapt livestock integration and crop rotation to the constraints and challenges of dryland agricultural production in the colder semiarid environments of the NGP. The short growing seasons and limited precipitation in this region are not conducive to growing cover crops and thus grazing livestock between harvest and spring planting (Unger and Vigil, 1998). In the NGP, livestock grazing could be used as an alternative way to manage fallow fields. Fallow ground is typically managed with either tillage or herbicides to conserve moisture and control weeds. Though effective, these practices have their limitations. First, tillage and herbicides represent a large and increasing portion of energy and input costs (Derksen et al., 2002). Second, tillage can result in soil erosion and decreased soil quality (Dickey et al., 1983; Schomberg and Jones, 1999). Finally, despite the effectiveness of herbicide-based programs in reducing tillage intensity and soil erosion, this approach to weed management is associated with growing economic, environmental, and societal

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**Abbreviations:** CSW, continuous spring wheat; FR-F-W; forage–fallow–spring wheat; NGP, Northern Great Plains.

concerns, including increased selection pressure for herbicide-resistant biotypes (Liebman and Staver, 2001). While the benefits of increasing crop diversity and cropping intensity in the NGP are well documented (e.g., Derksen et al., 2002; Blackshaw et al., 2008,), the interactions between livestock integration and crop rotation on crop production and weed management have been largely unexplored.

In the NGP, livestock can be used to directly consume and control weeds, not only during fallow years but also during fallow periods before planting and after harvest, thereby replacing tillage and herbicide. Annual weeds often are highly palatable to grazing ruminants (Marten and Anderson, 1975) and can have high nutritive value (Moyer and Hironaka, 1993; Nashiki et al., 2005). Small-bodied grazers, such as sheep and goats, are well-suited for integration into wheat production in the NGP as they are easily transported and confined, are common in the region, and consume a broad range of crop residues (Marten and Anderson, 1975). In addition, smaller ruminants distribute feces and urine more evenly across the field than cattle (Haynes and Willams, 1993; Abaye et al., 1997; Di and Cameron, 2007) and reduce insect pests, such as the wheat stem sawfly (*Cephus cinctus* Norton) (Goosey et al., 2005; Hatfield et al., 2007). To our knowledge, research on the use of livestock integration for weed control in agricultural fields has been restricted in perennial and small-scale vegetable crop production (summarized in Hilimire, 2011).

In 2004, we initiated a long-term crop rotation and integrated crop–livestock study at Montana State University. Our main goal was to examine the effects of integrated livestock and conventional fallow management practices (sheep grazing, minimum tillage, and conventional tillage) across a range of crop rotations. During the first 5 yr of this study, the rotations were CSW and wheat–fallow systems. Our results indicated that sheep-grazed systems resulted in wheat yields equivalent to conventional herbicide- and tillage-based systems (Sainju et al., 2011; Lenssen et al., 2013). This article reports the continuation and modification of the original study with the overall goal of increasing our knowledge base on the effects of crop diversification and grazing on spring wheat yields and quality (test weights and protein content) and weed abundance.

## MATERIALS AND METHODS

### Experimental Site

This study was conducted over 3 yr (2009–2011) at the Fort Ellis Research and Teaching Center, Montana State University, near Bozeman, MT (45°40′ N, 111°2′ W, altitude 1468 m). Soils at the site were a Blackmore silt loam (a fine-silty, mixed, superactive, frigid Typic Arguistoll) with 0 to 4% slopes and consisted of a 1:1:2 mixture of sand, clay, and silt by weight. Soils contained sufficient levels of plant-available P and K (>16 and 250 mg kg$^{-1}$for P and K, respectively) and only required N fertilization. Soil pH ranged from moderately acidic to slightly alkaline (5.5–7.5). Long-term (120-yr) mean monthly temperatures at the site range from −5.7°C in January to 19.0°C in July and annual precipitation averages 453 mm (Table 1).

Before 2004, the entire site was used for pasture for 10 yr and consisted of a mixture of perennial grasses. Between 2004 and 2008, wheat was grown in the area in a randomized split-plot design with summer fallow management treatments (grazed, chemical, and tillage) applied to plots and cropping system treatments (CSW, spring wheat–fallow, and winter wheat–fallow) assigned to split-plots (Sainju et al., 2011; Lenssen et al., 2013). In 2009, the wheat–fallow rotation was replaced with a 3-yr rotation of intercropped pea (*Pisum sativum* L.) and barley (*Hordeum vulgare* L.) used for a forage–fallow–spring wheat (FR-F-W) rotation, with each phase present every year (Table 2). The goal of this redesigned study was to provide increased cropping intensity, with the forage crop mixture selected to provide a high-quality feedstock (Chen et al., 2004) and additional source of soil N, increase weed suppression, and reduce herbicide use (Liebman and Dyck, 1993; Hauggaard-Nielsen et al., 2001). The CSW system was continued as a treatment to represent a common low-diversity, high-intensity cropping system.

### Experimental Design and Cropping Systems

In this study, fallow management practices (grazed, minimum tillage, and conventional tillage) were applied at the whole-plot level (0.55 ha in size, replicated three times) and were carried over from a previous experiment (Sainju et al., 2011; Lenssen et al., 2013) for logistical reasons and to examine

Table 1. Total monthly and annual precipitation and mean monthly air temperature from 2009 to 2011 at the experimental site.

| | Temperature | | | | Precipitation | | | |
|---|---|---|---|---|---|---|---|---|
| Month | 2009 | 2010 | 2011 | 120-yr avg. | 2009 | 2010 | 2011 | 120-yr avg. |
| | °C | | | | mm | | | |
| January | −2 | −3 | −3 | −6 | 4 | 13 | 12 | 21 |
| February | 0 | −2 | −6 | −4 | 9 | 8 | 3 | 18 |
| March | −1 | 3 | 2 | 0 | 37 | 25 | 16 | 33 |
| April | 4 | 5 | 3 | 6 | 69 | 37 | 57 | 46 |
| May | 12 | 8 | 8 | 10 | 41 | 83 | 41 | 71 |
| June | 13 | 14 | 14 | 15 | 64 | 115 | 79 | 72 |
| July | 19 | 19 | 20 | 19 | 68 | 10 | 17 | 33 |
| August | 18 | 18 | 20 | 18 | 38 | 44 | 24 | 31 |
| September | 17 | 13 | 16 | 13 | 13 | 39 | 16 | 42 |
| October | 3 | 10 | 9 | 7 | 45 | 17 | 33 | 38 |
| November | 2 | −2 | 0 | 0 | 29 | 34 | 16 | 27 |
| December | −8 | −4 | −3 | −4 | 7 | 15 | 9 | 22 |
| Annual total | – | – | – | – | 424 | 440 | 323 | 454 |

Table 2. The sequence of crops (phases) within cropping systems treatments during the experiment (2009–2011) and beforehand (2004–2008). Data presented here were collected in the spring wheat phases (SW) of both rotations.

| 2004–2008 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|
| Crop rotation | | Phases | | |
| Continuous spring wheat | SW | SW | SW | SW |
| Wheat–fallow rotations | fallow | forage | fallow | SW |
| | wheat | fallow | SW | forage |
| | fallow | SW | forage | fallow |

their long-term agronomic consequences. Main plots were divided into four, 0.14-ha subplots corresponding to different cropping systems. Subplots that were assigned to CSW treatments in 2004 were continued during this study. Subplots formerly in wheat–fallow rotations were assigned to each phase of the FR-F-W rotation. In this rotation, the annual forage consisted of a mixture of barley 'Hays' and field pea 'Arvika', followed by summer fallow, followed by spring wheat 'Vida' (Lanning et al., 2006). In 2009, the fallow and wheat phases of the FR-F-W rotation followed the wheat and fallow phases, respectively, of the previous rotation (Table 2). Consequently, observations obtained in 2009 and 2010 represent the sixth and seventh year of the effects of fallow management (grazed, chemical, and tillage) and cropping system (wheat–fallow and CSW) on wheat yields and weed abundance (Table 2). In 2011, the first year's wheat was grown after a complete FR-F-W diversified rotation, data were obtained in the CSW subplots and the spring wheat subplots of the 3-yr rotation within each fallow management plot (grazed, chemical, and tillage). After 2011, the experiment was terminated. Although we were only able to collect data for the effects of the FR-F-W rotation in the final year, it provided a unique opportunity to compare management practices across a long-term monoculture and a more diversified rotation.

## Crop Management Treatments

Within each fallow management treatment, different agronomic practices were used for weed and residue management (Table 3). Residual soil N was sampled in the fall (mid-October) of each year by taking and homogenizing five soil samples (4 cm in diameter, 60 cm depth) per subplot. The crops in the subsequent year were fertilized based on Montana State University fertilizer recommendations using yield goal, residual N, and crop type (Jacobsen et al., 2003). Spring wheat yield goals and target N rates were lower in CSW than in wheat following a fallow phase. Nitrogen fertilizer was added to attain 202 and 252 kg of N ha$^{-1}$, respectively. Fertilizer was applied at seeding as broadcast granular urea. Fertilizer was incorporated with shallow tillage. Minimum tillage treatment plots received an herbicide application of glyphosate [*N*-(phosphonomethyl) glycine] at 416 g a.i. ha$^{-1}$ and dicamba (3,6-dichloro-*o*-anisic acid) at 281 g a.i. ha$^{-1}$ 0 to 4 d before seeding. In the grazed treatment, 1 to 2 wk of sheep grazing was used for preplanting weed control, except in 2009 when weed pressure was low (<5% ground cover). Sheep grazed until weed biomass was reduced below 5% ground cover (approximately 47 kg ha$^{-1}$), based on visual assessment. Preplanting stocking rates (mean of 484 sheep-days ha$^{-1}$) varied slightly depending on weed pressure and precipitation. In conventional tillage treatments, no additional preplanting management was applied.

Planting dates were typical for this area: 19 May 2009, 17 May 2010, and 16 May 2011. All crops were planted at 15-cm row spacing. Spring wheat was seeded at a rate of 89.7 kg seed ha$^{-1}$. In spring wheat, postemergence herbicide applications were determined by weed identity and density and varied by year and management treatment. In 2009, no in-crop herbicides were applied. In 2010, all plots were sprayed with a tank mixture of dicamba and pinoxaden [8-(2,6-diethyl-*p*-tolyl)-1,2,4,5-tetrahydro-7-oxo-7*H*-pyrazolo(1,2-*d*)(1,4,5)oxadiazepin-9-yl 2,2-dimethylpropionate] at 140 and 30 g a.i. ha$^{-1}$, respectively, 4 wk after seeding. In 2011, no herbicides were applied in minimum tillage and conventional tillage managed spring wheat in the FR-F-W rotation. In-crop herbicides were applied in grazing-managed spring wheat in the FR-F-W rotation and all CSW subplots. In grazing-managed spring wheat, weeds were controlled with dicamba (140 g a.i.ha$^{-1}$) 3 wk after seeding and pyrasulfotole [(5-hydroxy-1,3-dimethylpyrazol-4-yl)($\alpha$,$\alpha$,$\alpha$-trifluoro-2-mesyl-*p*-tolyl)methanone] and bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) at 41 and 230 g a.i ha$^{-1}$,

Table 3. Description of crop and fallow management practices used within each cropping system, phase, and management treatment. Fallow management differed in the fallow phase and in the preplanting and postharvest periods.

| Cropping system† | Phase | Management treatment | Preplanting practices | Postharvest practices |
|---|---|---|---|---|
| FR-F-W | forage | minimum tillage | glyphosate and dicamba applied | forage baled and removed‡ |
| | | conventional tillage | | forage baled and removed‡ residues incorporated with tillage |
| | | grazing | grazing§: 549–586 sheep-days ha$^{-1}$ | swath-grazed¶: 1026 to 1281 sheep-days ha$^{-1}$ |
| WF and FR-F-W rotations | fallow | minimum tillage | herbicides (glyphosate and dicamba tank mix applied at 416 and 281g a.i. ha$^{-1}$, respectively) | |
| | | conventional tillage | tilled with a JD 100 field cultivator (Deere&Co., Moline, IL) fitted with 15-cm-wide sweeps | |
| | | grazing | grazed: 234–498 sheep days ha$^{-1}$ | |
| WF, FR-F-W, and CSW rotations | spring wheat | minimum tillage | glyphosate and dicamba applied | residues were incorporated with tillage |
| | | conventional tillage | | residues were incorporated with tillage |
| | | grazing | grazing: 176–344 sheep-days ha$^{-1}$ | Grazed residues: 659–806 sheep-days ha$^{-1}$ |

† WF, wheat–fallow rotation; FR-F-W, forage–fallow–wheat rotation; CSW, continuous spring wheat.

‡ Postharvest application of glyphosate (416 g a.i. ha$^{-1}$) in 2009.

§ Treatment was not applied in 2009.

¶ In 2009, forage was swathed and baled; sheep grazed the residue and stubble.

respectively, applied 4 wk after seeding. In CSW, grassy weeds were controlled with pinoxaden (74 g a.i. ha$^{-1}$) applied 6 wk after seeding.

Postharvest crop residue and weed management also differed across management treatments and previous crops (Table 3). In all management treatments, spring wheat straw was windrowed and baled following harvest, a typical management practice in this area. In grazed treatments, sheep grazing was used for residue reduction and incorporation after straw was removed. Postharvest grazing in spring wheat was not applied in 2009. In minimum tillage and conventional tillage treatments, residues were incorporated with shallow tillage.

In the forage crop phase of the FR-F-W rotation, barley and pea were seeded at 50.5 and 112 kg seed ha$^{-1}$, respectively. No postemergence herbicides were applied, as one of the objectives of the forage phase was to reduce herbicide use by planting a competitive mixture and few in-crop herbicides exist that were safe for both crops. In this phase, harvest and postharvest practices differed among the three management treatments. In the minimum tillage and conventional tillage treatments, the forage crop was swathed, windrowed, baled, and removed. These treatments received a postharvest (mid-August) application of glyphosate (416 g a.i. ha$^{-1}$) in 2009. In the conventionally tilled treatments, residues were incorporated with an offset disk. In grazed treatments, the forage crop was windrowed and grazed by sheep. In 2009, postharvest grazing differed, as intensive rain fell on the windrowed crop, resulting in moldy, unpalatable forage. The forage crop was baled and removed and sheep were grazed on stubble. In subsequent years, mature white-faced ewes were kept on plots for 2 to 3 wk until standing and windrowed forage was exhausted.

Management of the summer fallow phase varied across the three management treatments. Under conventional tillage, the fallow phase was tilled; in the minimum tillage plots, herbicides were applied (Table 3). In the grazed treatment, the fallow phase was grazed until weed biomass was less than 5% ground cover (approximately 47 kg ha$^{-1}$) based on visual assessment. Sheep stocking rates varied depending on weed biomass and precipitation (Table 3). Typically, grazing bouts consisted of 8 to 14 mature sheep on a subplot for 4 to 6 d. White-faced rams, ewes, and wethers were used to graze fallow fields, depending on availability. All fallow management treatments were applied every 4 to 6 wk from June until September, depending on weed abundance.

## Data Collection

Wheat was harvested on 22 Sept. 2009, 4 Oct. 2010, and 13 Sept. 2011 using a combine harvester (Kincaid 2045, Haven, KS). Total grain production was measured for each plot using a portable load scale Flexweigh scale (Enduro Systems, Santa Rosa, CA). Yields were adjusted to 12% moisture content for analysis. Random subsamples of grain from each subplot were obtained and grain N concentration was determined by near-infrared spectroscopy; grain protein concentration was calculated by multiplying N concentration by 5.7. Grain test weight was determined with a Grain Analysis Computer (Dickey-john Corp., Minneapolis, MN).

Weed density and community diversity in spring wheat plots were estimated four times at 2-wk intervals during the first half of the growing season (late May to early July) in 2010 and 2011. For each sampling date, three randomly located 1 m$^2$ quadrats were placed in each wheat subplot. Within each quadrat, visual estimates of percentage of cover were recorded for each weed species and weeds species were grouped into annual and perennial functional groups. Species richness (number of species per m$^2$) and percentage of cover were averaged across sampling dates. These metrics were used to estimate early-season weed pressure, as they integrate competitive weed pressure during the period when weeds' impacts on yields are greatest (Cousens et al., 1987) while accounting for differences in the timing of emergence and growth among weed species. For each weed species, relative abundance was calculated as their percentage of total weed cover within a given treatment.

## Statistical Analysis

In 2009 and 2010, we compared wheat yields, wheat quality, percentage of weed cover, and weed species richness between the CSW and the spring wheat–fallow rotation using a split-split-plot ANOVA. In this model, fallow management practice (grazed, minimum tillage, and conventional tillage) was a fixed main-plot factor and block was a random main-plot factor. Cropping system treatment (continuous and rotated crops) and the interaction between fallow management and cropping system treatments were the split-plot factors. Year and interactions among year and experimental treatments were analyzed as the repeated measures within the split-plots (split-split-plot). In 2011, spring wheat was preceded by all phases of the FR-F-W rotation and data were analyzed using a separate split-plot ANOVA. Differences among treatments were tested using Tukey's honest significant difference. Parameters of the post-hoc test (replication per treatment, mean squared error, and mean squared error df) were adjusted for each level of the analysis. Equality of variances was tested using Levene's test, calculated based on the median value for each treatment level in each year.

An analysis of covariance model was used to test if differences in early season weed percentage of cover explained the effects of management treatments on spring wheat yields. To select the best-fit model, a stepwise backward elimination of terms was employed based on the Akaike Information Criterion. The initial model included all possible interactions among fixed effects of cropping system treatment and year to control for differences in weed-free yields (i.e., estimated intercept terms) in each treatment, year, and weed biomass estimate. The proportion of variation in yields explained by weed abundance was calculated as the ratio of the variance (sum of squares) of terms that included weed biomass to the total sum of squares, excluding the effects of cropping system and year. All analyses were conducted using R statistical software (R Development Core Team, 2008).

# RESULTS

## Climate

Climatic conditions during the experiment consisted of two relatively wet years followed by dry conditions in 2011 (Table 1). Cumulative precipitation from April to July was 242 and 245 mm in 2009 and 2010, respectively. These values are near the long-term average but higher than the average over the last decade. In 2011, 194 mm of precipitation fell during the same period, 50 mm less than the previous 2 yr and similar to the conditions observed at the site from 2004 to 2008. Mean monthly temperatures throughout this study were similar to the long-term averages (Table 1).

## Spring Wheat Grain Yield and Quality

Consistent with the results from the initial set of treatment comparisons (Lenssen et al., 2013), during the first 2 yr of this study, integrating grazing into wheat–fallow and CSW rotations resulted in wheat yields that were similar to those observed in the conventional tillage and minimum tillage management treatments (Table 4). The differences among crop rotation treatments were varied by year. A yield advantage of the wheat–fallow rotation over CSW was evident in 2010 but not in 2009 (Table 4). During the same period, protein content was not affected by fallow management or cropping system treatments ($p > 0.2$), with values ranging from 14.1 to 14.9%. Grain protein content was consistent between 2009 and 2010 in CSW but differed among years in the wheat–fallow rotation (cropping system × year interaction, $p < 0.01$) with a small yet significant increase from 2009 to 2010. Grain test weights were influenced only by crop rotation treatments ($F_{1,6} = 8.62, p < 0.05$) and were higher in CSW (mean = 805 kg $m^{-3}$) than in the wheat–fallow rotation (mean = 801 kg $m^{-3}$). Test weights of all samples met the requirements for highest classification (Grade 1) set by the USDA (minimum test weight = 770 kg $m^{-3}$).

In 2011, when the cropping systems comparisons consisted of CSW vs. the FR-F-W rotation, and in accordance with the result observed in 2010, grain yield was greater for spring wheat following summer fallow than for the CSW system (Table 4). In contrast to the results observed during the first 2 yr of this study, management treatments did impact yields and these impacts tended to vary among cropping systems ($p < 0.1$,Table 4). The negative impacts of grazing on wheat yields tended to be particularly large in the 3-yr rotation (Table 4), where using sheep grazing to manage weeds and residues was associated with a 51% yield reduction compared to conventional tillage or minimum tillage management. Yields in grazing-managed spring wheat in the diversified cropping system were similar to yields in CSW regardless of management treatment (Table 4). In CSW, the effects of grazing-based management on yields tended to be less than in the FR-F-SW rotation and yields were similar among management treatments in post-hoc comparisons. In addition, when the analysis was restricted to CSW and yields were pooled across the 3-yr study, there were no significant effects of management ($F_{2,4} = 1.4, p > 0.3$), nor was there evidence that these management effects were greater in 2011 (management treatment × year, $F_{4,12} = 1.5, p > 0.2$). Grain protein content was similar among management ($p > 0.6$) and cropping system ($p > 0.1$) treatments, with a mean of 14.8%. As before, test weights were greater in CSW (mean = 796 kg $m^{-3}$) than in the 3-yr rotation (mean = 779 kg $m^{-3}$, cropping system main effect $F_{1,6} = 13.3, p < 0.05$).

## Weed Diversity and Abundance

The weed community consisted of one or two dominant species that varied among years and treatments (Table 5). In 2010, 14 weed species were observed, with similar species dominating the conventional tillage and minimum tillage wheat–fallow rotations (Table 5). The majority (59%) of the total weed cover pooled across these two treatments was composed of redroot pigweed (*Amaranthus retroflexus* L.), field pennycress (*Thlaspi arvense* L.), and henbit (*Lamium amplexicaule* L.). In the grazing-managed wheat–fallow rotation, dandelion (*Taraxacum officinale* F. H. Wigg.) was the dominant weed, comprising over half of the weed cover. Dandelion was also the dominant weed species in grazing-managed CSW treatments. Redroot pigweed and common lambsquarters (*Chenopodium album* L.) were the dominant weed species in CSW of the conventional tillage and minimum tillage management treatments (Table 5).

Table 4. Spring wheat yields in two cropping systems and three fallow management treatments [grazing, conventional tillage (CT), or minimum tillage (MT)] for 3 yr.

| Year | Yields 2009 | 2010 | 2011 |
|---|---|---|---|
| | | Mg $ha^{-1}$ | |
| Continuous spring wheat | 5.23a‡ | 3.17b | 1.73 |
| MT | 4.96 | 3.02 | 1.80c |
| Grazing | 5.08 | 3.05 | 1.18c |
| CT | 5.65 | 3.45 | 2.20cb |
| Alternate rotation† | 5.03a | 4.95a | 2.67 |
| MT | 5.07 | 5.30 | 3.11ab |
| Grazed | 4.90 | 4.16 | 1.57c |
| CT | 5.17 | 5.38 | 3.32a |
| Significance§ | | P > F | |
| F | NS | | * |
| CS | *** | | *** |
| F × CS | NS | | MS |
| Y | *** | | |
| F × Yr | NS | | |
| CS × Y | *** | | |
| F × CS × Y | NS | | |

* Significant at the $p < 0.05$ level.

*** Significant at the $p < 0.001$ level.

† In 2009 and 2010, the alternate crop rotation consisted of wheat–fallow. In 2011, wheat was grown following all phases of a forage–fallow–wheat rotation.

‡ Experiments were analyzed separately. Within each experiment, means followed by a different letter differed in post-hoc tests (Tukey's honest significant difference = 0.70 for interaction between cropping system and year in 2009 and 2010 and 0.99 for the interaction between management and cropping system in 2011).

§ MS, significance at the $0.05 < p < 0.1$ level; NS, not significant (i.e., $p > 0.1$); F, fallow management; CS, cropping system; Y, year.

In 2011, 18 weed species were present in wheat plots. As in 2010, dominant weed species varied with management and cropping systems treatments. Four weed species dominated the weed community in the grazing-managed FR-F-W rotation: dandelion, shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.], lambsquarters, and common mallow (*Malva neglecta* Wallr.). These four species comprised between 84 and 90% of the total weed cover across sampling dates in the grazed plots. In the conventional tillage or minimum tillage managed FR-F-W rotations, shepherd's purse and field pennycress were the dominant weed species, comprising over 50% of the weed cover (Table 5). Dominant weed species also varied with management in CSW. In grazing-managed CSW, dandelion and prickly lettuce (*Lactuca serriola* L.) made up 61% of the total weed cover, whereas in minimum tillage CSW, the majority of the weed cover comprised two species, western rockjasmine (*Androsace occidentalis* Pursh) and shepherd's purse. wild oat (*Avena fatua* L.) was the dominant weed in conventionally tilled CSW.

The effects management treatments on total weed cover varied by cropping system or rotation treatment and this effect

Table 5. Richness and dominance of weed species in spring wheat across management and cropping system treatments.†

| Year | Management | Cropping system | Weed species‡ | RA | Weed species | RA | Weed species | RA |
|---|---|---|---|---|---|---|---|---|
| | | | | % | | % | | % |
| 2010 | Grazing | WF | dandelion | 55.4 | prickly lettuce | 11.2 | black medick§ | 9.6 |
| | MT | WF | henbit | 35.0 | pigweed | 30.0 | field pennycress | 10.0 |
| | CT | WF | field pennycress | 42.9 | prickly lettuce | 14.3 | 3 species | 9.5 |
| | Grazing | CSW | redroot pigweed | 30.0 | dandelion | 20.0 | henbit | 15.0 |
| | MT | CSW | common lambsquarters | 28.2 | pigweed | 25.6 | henbit and slender Collomia¶ | 15.4 |
| | CT | CSW | redroot pigweed | 36.5 | lambsquarters | 15.4 | common mallow# | 15.4 |
| 2011 | Grazing | FR-F-W | dandelion | 36.6 | lambsquarters | 23.3 | shepherd's purse | 18.4 |
| | MT | FR-F-W | shepherd's purse | 59.6 | dandelion | 10.5 | prickly lettuce | 7.0 |
| | CT | FR-F-W | field pennycress | 52.2 | pigweed | 13.0 | 3 species | 8.7 |
| | Grazing | CSW | dandelion | 46.1 | prickly lettuce | 15.3 | shepherd's purse | 15.1 |
| | MT | CSW | western rockjasmine | 31.5 | shepherd's purse | 24.1 | dandelion | 13.0 |
| | CT | CSW | wild oat | 62.8 | field pennycress | 30.1 | pigweed | 5.7 |

† RA, relative abundance, defined as the percentage of the total weed cover within a given treatment of that weed species; MT, minimum tillage; CT, conventional tillage; WF, wheat–fallow; CSW, continuous spring wheat; FR-F-W, forage–fallow–wheat rotation.

‡ Species are listed from left to right by their relative abundance.

§ *Medicago lupulina* L

¶ *Collomia linearis* Nutt.

# *Malva neglecta* Wallr.

differed between 2010 and 2011 (management × cropping system × year $F_{2,12} = 6.1, p < 0.05$). Weed increases associated with grazing were larger wheat–fallow and FR-F-W rotations than in CSW plots. In 2010, grazing-based management in the wheat–fallow rotation resulted in a nearly 10-fold increase in weed cover relative to other management treatments (Table 6). In 2011, grazing was associated with a nearly 30-fold increase in weed cover relative to the other management treatments in the FR-F-W rotation. Conversely, in CSW, grazing was not consistently associated with increases in weed cover relative to minimum and conventional tillage management treatments.

Annual and perennial weeds exhibited unique responses across weed management and cropping systems. Effects of management on annual weed biomass varied by cropping system and year (management × cropping system × year; $F_{2,12} = 10.95, p < 0.005$). In 2010, annual weed biomass was similarly low across all management treatments and cropping systems (Table 6). However, in 2011, the grazing was associated with an increase in annual weeds in the FR-F-W rotation but not in CSW. Increases in the abundance of perennial weeds were more consistently associated with graze-based management, particularly in the rotations that included a grazing-fallow phase (management × cropping system; $F_{2,6} = 11.2, p < 0.01$) and more so in 2011 than in 2010 (management × year; $F_{2,12} = 16.4, p < 0.001$; Table 6). In contrast, perennial weeds were rare or absent in the other management treatments throughout the experiment. Treatments had similar effects on weed species richness and weed cover. Weed species richness in the grazing-managed, wheat–fallow, and FR-F-W rotations was greater than in the minimum tillage and conventionally tilled spring wheat (Table 6).

## Weed Cover and Spring Wheat Yield Relationship

Within each cropping system and year, differences in early season weed pressure explained the majority of the variation in yields among management treatments. The best-fit model of spring wheat yields included the differences in weed-free yields in each cropping system in each year (year × cropping system interaction terms) and the negative effects of percentage of

Table 6. Weed percentage ground cover and diversity in management treatments for each cropping system treatment and year. Weed abundance is presented as percentage of cover for all functional groups (total, annual, and perennial weeds).†

| | Alternate rotation | | | Continuous spring wheat | | |
|---|---|---|---|---|---|---|
| Year | MT | Grazing | CT | MT | Grazing | CT |
| | | | Mean total weed percentage of ground cover | | | |
| 2010‡ | 1.11 AB§ | 8.28 B | 0.58 A | 1.22 AB | 1.17 A | 1.67 AB |
| 2011 | 1.36 AB | 28.70 D | 0.68 A | 4.74 ABC | 12.00 C | 2.22 AB |
| | | | Mean annual weed cover | | | |
| 2010 | 1.11 A | 2.64 AB | 0.58 A | 1.08 A | 0.86 A | 1.67 AB |
| 2011 | 0.97 A | 16.90 C | 0.65 A | 3.99 AB | 6.38 B | 2.22 AB |
| | | | Mean perennial weed cover | | | |
| 2010 | 0.00 A | 5.60 B | 0.00 A | 0.14 A | 0.31 A | 0.00 A |
| 2011 | 0.39 A | 11.90 C | 0.03 A | 0.75 A | 5.65 B | 0.00 A |
| | | | Weed species richness (species $m^{-2}$) | | | |
| 2010 | 0.64 A | 1.67 BC | 0.44 A | 0.64 A | 0.78 AB | 0.78 AB |
| 2011 | 0.94 ABC | 2.53 D | 0.56 A | 1.92 CD | 1.39 ABC | 0.89 AB |

† MT, minimum tillage; CT, conventional tillage.

§ Within each weed measure, means followed by a different uppercase letter were different in post-hoc tests.

‡ In 2010, the alternate crop rotation consisted of a wheat–fallow rotation. In 2011, it was a 3-yr wheat–barley and field pea–summer fallow rotation.

Table 7. Results of the analysis of covariance model assessing the correlation between early-season weed pressure and wheat yields.†

| Source | df | Mean square | F | p value |
|---|---|---|---|---|
| W | 1 | 15.0 | 39.1 | *** |
| Y | 1 | 19.9 | 78.3 | *** |
| CS | 1 | 20.7 | 81.3 | *** |
| W × Y | 1 | 0.4 | 1.4 | NS |
| Y × CS | 1 | 1.6 | 6.4 | * |
| Error | 30 | 0.3 | – | – |

* Significant at the $0.05 > p > 0.01$ level.

*** Significant at the $p < 0.001$.

† NS, $p > 0.1$; W, weed percentage of ground cover; Y, year, CS, cropping system.

weed cover on yields (Table 7). Slope estimates indicated that yields decreased by 0.14 Mg ha$^{-1}$ for each percentage increase in weed cover. Excluding the variation in yields explained by cropping systems and year, the negative impacts of weeds on spring wheat yields explained 67% of the remaining variance among yields across management treatments (Table 7).

## DISCUSSION

Small-grain production in the NGP is threatened by an increased prevalence of herbicide-resistant weeds and losses in soil quantity and quality (Derksen et al., 2002). Integrating crop and livestock production and increasing rotational diversity are promising methods of diversifying management practices and improving economic and environmental sustainability (Davis et al., 2012). Although tradeoffs exist when incorporating livestock into cropping systems (Fisher et al., 2012), it has the potential of reducing input costs and risks associated with tillage and herbicide application while increasing economic returns for producers through the added value of animal production and reduced feed costs (Karn et al., 2005; Franzluebbers and Stuedemann, 2007), particularly in water-limited environments (Bell et al., 2014; Johnson et al., 2013).

Our research provides new insights into the integration of livestock grazing into semiarid cropping systems in several ways. First, although previous research conducted in other regions of North America has assessed the impacts of cattle grazing on crop yields and weed control, we used sheep, a species that is well suited for integration in the NGP. Second, we used sheep to control weeds in the context of crop diversification, whereas previous studies used livestock to graze residues and cover crops (Tracy and Davis, 2009). Third, although previous research compared diversified integrated systems to conventional monocultures, our study is unique, as it was designed to isolate the unique and interactive effects of livestock integration and cropping systems diversification on yields and weed pressure.

In this study, grazing resulted in similar yields and grain quality to conventional tillage and minimum tillage management in CSW and wheat–fallow rotations. These results are consistent with studies conducted at the same experimental site (Sainju et al., 2011; Lenssen et al., 2013) and demonstrate the long-term (7-yr) efficacy of an integrated livestock–wheat production system. The results also suggest that grazing-based management provides yields similar to conventional and reduced tillage even in conditions of higher yield potential. In 2009 and 2010, growing season precipitation was greater than in any year between 2005 and 2008 and yields increased substantially. Yields in wheat–fallow rotations in 2009 and 2010 were 2 Mg ha$^{-1}$ greater than the mean yields in the same rotation recorded in the previous 4 yr (Lenssen et al., 2013). Similar increases of 0.8 and 2.8 Mg ha$^{-1}$ were observed in CSW relative to the prior, dryer 4 yr (Sainju et al. (2011).) In the wheat–fallow rotation, grazing was associated with increased weed cover and species richness, particularly of perennial weed species, but these increases were relatively small and did not affect yields. Overall, our results indicate that grazing during the fallow phase of wheat–fallow rotations can significantly reduce the use of tillage and herbicides. For example, in the wheat–fallow rotation, the frequency of herbicide and tillage use was reduced by 75 to 80% in the grazing managed systems.

In contrast, when the forage crop was added to diversify the rotation, grazing-based management resulted in large yield reductions relative to conventional tillage and minimum tillage fallow management, effectively eliminating any potential yield advantage of the FR-F-W rotation over CSW. Longer-term experiments are required to draw definitive conclusions concerning the efficacy of this diversified integrated system. However, the yield reductions associated with grazing in the FR-F-W rotation appear to be caused by interactions of environmental conditions, including increased spring rainfall in 2009 and 2010 relative to the previous 5 yr, the pre-existing weed community, and the absence of herbicide use in the forage crop phase. The presence of livestock during these relatively wet years and in the phases before the spring wheat phase grown in 2011 may have reduced yields due to soil compaction. Livestock impacts on wet soils are known to lead to compaction, reduced water infiltration, and subsequent reductions in crop yields (Krenzer et al., 1989; Worrell et al., 1992). In a previous study conducted at this site, sheep grazing in the fallow phase increased soil compaction and reduced soil water content (Lenssen et al., 2013).

In addition, the yield losses associated with grazing-based management in the FR-F-W rotation appear to be linked to the interactive effects of management and climate on weed abundance. Wheat that was managed with grazing in the diversified FR-F-W rotations increased the abundance of dandelion, a perennial weed that is problematic in perennial pastures, lawns, and annual crops across the NGP (Stewart-Wade et al., 2002; Froese and Van Acker, 2003; Leeson et al., 2005). Infestations of dandelion are not effectively controlled with in-crop herbicides but are more easily managed by glyphosate applied later in the season (Hacault and Van Acker, 2006). Also, it is possible that increased abundance of dandelion observed in grazing-managed treatments were related to the wet conditions during 2009 and 2010. Evidence suggests that wet spring and midsummer conditions are required for seedling survival and growth in dandelion (Blackshaw et al., 2001; Hacault and Van Acker, 2006).

In addition to perennial weeds, annual weeds were also abundant in grazing-managed wheat in the FR-F-W rotation. According to our observations, this was probably the result of increased seedbank due to higher weed seed production in forage and fallow phases of the grazing-managed treatments compared to minimum and conventional tillage management.

Overall, our results suggest that grazing-based management can reduce tillage intensity and herbicide use and provide similar yields to conventional tillage or minimum tillage management in CSW and wheat–fallow rotations. However, the optimal integration of grazing and diversified cropping systems in the NGP may require additional weed management practices or alternative crop rotations. Alternative forage crop management (Lenssen, 2008) or selection and longer duration of the forage phase within the rotation, in conjunction with higher seeding rates and narrow row spacing, could provide better weed control (Entz et al., 1995; Blackshaw et al., 2008). Finally, farmers facing increased weed pressure in these diversified grazed systems could occasionally replace preplanting, fallow, and postharvest grazing with herbicide applications. For example, a single glyphosate application following the forage phase or at the end of the fallow phase may have controlled the dominant perennial weeds in the grazing-managed systems and prevented the yield losses observed. In summary, grazing can be used to reduce tillage and herbicide use but weed pressure should be monitored and controlled using integrated and effective practices.

## CONCLUSIONS

Using sheep grazing to replace herbicide- or tillage-based weed and residue management practices in CSW and wheat–fallow rotations can consistently provide similar spring wheat yields and grain quality to conventional management systems. Consequently, integration of livestock into wheat production in the NGP has the potential to reduce the costs and risks of tillage and herbicide use. However, in the last year of this study, when combined with a more diversified FR-F-W rotation, livestock integration resulted in large increases in weed pressure and yield losses. Although a long-term study is required to validate this result, it appears to be driven by interactions among environmental conditions, weed pressures, and grazing. Though challenging, the integration of livestock grazing into diversified cropping systems can help in the quest of designing environmentally sustainable and economically viable management systems.

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