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Abstract

Sheep (*Ovis aries* L.) grazing, a cost-effective method of controlling weeds compared to herbicide application and tillage, may influence soil C and N levels by consuming plant residue and returning feces and urine to the soil, but little is known about the practice on soil C and N storage under dryland cropping systems in the northern Great Plains, USA. Three weed control practices [sheep grazing (GRAZ), herbicide application (CHEM), and tillage (MECH)] and three cropping sequences [continuous alfalfa (*Medicago sativa*L.) (CA), continuous spring wheat (*Triticum aestivum* L.) (CSW), and spring wheat-pea (*Pisum sativum*L.)/barley (*Hordeum vulgaris* L.) hay mixture-fallow (W-P/B-F)] were evaluated on a Blackmore silt loam from 2009 to 2011 in southwestern Montana, USA. Crop yields and soil organic C (SOC), total N (STN), NH_4-N, and NO_3-N contents at the 0–120 cm depth were quantified. Annualized spring wheat grain and biomass (stems + leaves) yields and C and N contents were greater with CSW than with W-P/B-F, but hay biomass and C content were similar between CA and W-P/B-F. While C and N in aboveground biomass after spring wheat and hay harvest were removed through haying in CHEM and MECH, sheep grazing removed about 99% of these elements in GRAZ. The SOC and STN at 5–15 cm were greater with CSW or W-P/B-F than with CA in GRAZ and MECH, but SOC at 30–60 cm was greater with CA than with CSW in MECH. The NH_4-N content at most depths varied among treatments and years, but NO_3-N content at 5–120 cm was greater with CSW and W-P/B-F than with CA. Longer duration of sheep grazing during fallow periods due to increased return of C and N through feces and urine or residue incorporation to a greater depth probably increased soil C and N storage at the surface layer with CSW and W-P/B-F in GRAZ and MECH, but increased root biomass likely increased C storage at the subsurface layer with CA in MECH. Absence of N fertilization and/or greater N uptake probably reduced soil NO_3-N level with CA than with other cropping sequences. Regardless of treatments, SOC and STN declined from 2009 to 2011, probably due to residue removal from haying and grazing. Moderate sheep grazing during fallow periods can be used to increase soil C and N storage, obtain farm C credit, and sustain dryland crop yields compared to herbicide application for weed control in the semiarid regions.

Keywords

Cropping sequence, Dryland crop yields, Sheep grazing, Soil carbon, Soil nitrogen, Tillage

Disciplines

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Crop yields and soil organic matter responses to sheep grazing in US northern Great Plains

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ABSTRACT

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1. Introduction

In dryland cropping systems in the northern Great Plains, USA, sheep grazing during fallow periods (before crop planting, after grain harvest, and during summer fallow) is often used to control weeds, diseases, and insects, reduce feed cost, and increase nutrient cycling (Johnson et al., 1997; Entz et al., 2002). Alternate-year fallowing can conserve soil water, release plant nutrients, control weeds, increase succeeding crop yields, and reduce the risk of crop failure (Aase and Pikul, 1995; Jones and Popham, 1997). Although effective in controlling weeds, tillage and herbicide application are expensive, resulting in some of the highest variable costs for small grain production in Montana (Johnson et al., 1997). Other disadvantages of tillage and herbicide application are the exposure of soil to erosion due to tillage and increased risk of contamination by herbicides in soil, water, and air that are hazardous to human and animal health (Fenster, 1997). Sheep grazing during fallow periods is a cost-effective method of controlling weeds that can reduce soil erosion compared to tillage when enough amount of crop residue is left on

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the ground with moderate grazing without environmental degradation (Johnson et al., 1997; Entz et al., 2002).

Integrated crop and livestock systems have been recognized as one management strategy to improve soil and environmental quality by increasing C and N sequestration, reducing N fertilization rate, N leaching, and N_2O (greenhouse gas) emissions, and sustaining crop yields and quality (Franzluebbers, 2007; Maughan et al., 2009). In the northern US Great Plains, for example, allowing sheep to graze land during fallow periods (i.e. before crop planting, after grain harvest, and during summer fallow) can help control weeds, reduce feed cost, and increase nutrient cycling (Johnson et al., 1997; Entz et al., 2002). The integrated system can also have many other benefits including crops, meat, milk, and manure production, and weed and insect control for subsequent crops (Franzluebbers, 2007; Hatfield et al., 2007a, 2007b; Herrero et al., 2010). Animal grazing can influence C and N cycling by removing crop and weed residues and returning C and N inputs to the soil through feces and urine (Abaye et al., 1997; Franzluebbers and Studemann, 2008; Sainju et al., 2010). Several researchers (Franzluebbers and Stuedemann, 2008; Li et al., 2008) have reported that moderate grazing can increase soil organic matter (SOM) but heavy grazing can reduce its level. With proper management, grazing can increase soil quality and crop yields compared to non-grazing (Tracy and Zhang, 2008; Maughan et al., 2009). Uneven distribution of feces and urine by animals during grazing can be detrimental to the crop growth, however, distribution can be more uniform with sheep than with cattle (*Bos taurus* L.) grazing (Abaye et al., 1997)).

Hatfield et al. (2007a) and Snyder et al. (2007) reported that sheep grazing during fallow to control weeds did not influence SOM, NO_3-N content, and wheat yields compared to non-grazed treatment in western Montana. Abaye et al. (1997) found that grazing sheep and cattle together increased soil bulk density and organic matter and grass yields compared to grazing sheep or cattle alone.

Traditional dryland farming practices with conventional tillage and wheat-fallow systems in the northern Great Plains have reduced annualized crop yields and SOM due to the absence of crops during the fallow period and increased soil erosion and C and N mineralization (Aase and Pikul, 1995; Halvorson et al., 2002; Sainju et al., 2009b). While intensive tillage increases the oxidation of SOM (Bowman et al., 1999; Schomberg and Jones, 1999), fallowing reduces it by reducing the amount of crop residue returned to the soil and increasing soil temperature and water content, which subsequently increase microbial activity (Campbell et al., 2000; Halvorson et al., 2002). Increasing the fallow period by reducing the cropping intensity can reduce soil water storage efficiency and SOM while enhancing saline seeps development (Tanaka and Aase, 1987; Black and Bauer, 1988). In contrast, reducing tillage and increasing cropping intensity can increase crop yields and SOM (Aase and Pikul, 1995; Halvorson et al., 2002; Sainju et al., 2009b).

Tillage and cropping system can influence soil mineral N level through N mineralization, uptake, and leaching. No-till continuous cropping can increase crop yields compared to conventional till crop-fallow by increasing N uptake and reducing N losses, primarily through leaching (Aase and Pikul, 1995; Halvorson et al., 2000; Sainju et al., 2009a, 2009b). In contrast, conventional till and fallow can increase soil mineral N level at the cost of organic N due to increased N mineralization (Sainju et al., 2009a). Crop rotations that include forages and legumes with cereals can sustain yields and increase water- and N-use efficiency by improving soil water content and N availability compared to monocropping (Entz et al., 2002; Pikul and Aase, 2003; Lenssen et al., 2010). Legumes can reduce N fertilization rates for succeeding crops compared to nonlegumes (Sainju and Lenssen, 2011) by supplying greater levels of mineral N due to higher turnover rates of plant residue as a result of lower C/N ratios (Franzluebbers et al., 1995; Kuo et al., 1997).

Little information is available on the effect of sheep grazing compared to tillage and herbicide application for weed control on dryland soil C and N levels to a depth of 120 cm and crop yields under dryland cropping systems in the northern Great Plains. Based on our study, we hypothesized that sheep grazing would increase dryland soil C and N levels and crop yields compared to tillage or herbicide application and that the effect would be pronounced more with CA and CSW than with W-P/B-F. Our objective was to evaluate the effects of three fallow management practices for weed control (CHEM, GRAZ, and MECH) and three cropping sequences (CA, CSW, and W-P/B-F) on dryland crop grain and biomass yields, C and N contents, as well as SOC, STN, NH_4-N, and NO_3-N contents at the 0–120 cm depth from 2009 to 2011 in the southwestern Montana, USA.

2. Materials and methods

2.1. Site and treatment descriptions

The experiment was conducted from 2009 to 2011 at the Fort Ellis Research and Extension Center, Montana State University (45°40′ N, 111°2′ W; altitude 1468 m), approximately 8 km east of Bozeman, MT, USA. Total annual precipitation (113-yr average) is 465 mm and mean monthly air temperature ranges from −5.6 °C in January to 19 °C in July (Table 1). The soil is a Blackmore silt loam (fine-silty, mixed, superactive, frigid Typic Argiustolls) derived from calcareous loess with 0 to 4% slope, and contains 250 g kg^{-1}

Table 1
Monthly total precipitation and average air temperature at the experimental site from 2009 to 2011.

Month	Precipitation (mm)				Temperature (°C)			
	2009	2010	2011	113-yr avg.	2009	2010	2011	113-yr avg.
January	6	26	20	22	−2.0	−4.0	−3.8	−5.6
February	15	16	19	19	0.0	−2.9	−5.9	−3.7
March	62	40	30	34	−1.2	2.9	1.9	0.0
April	119	59	49	46	4.3	5.6	3.4	5.6
May	59	94	91	73	11.9	7.7	8.7	10.4
June	75	123	88	74	13.4	13.8	13.9	14.6
July	56	11	32	35	19.0	18.2	19.6	19.0
August	48	69	23	32	18.1	17.5	19.6	18.3
September	20	56	18	44	16.8	13.8	15.7	12.9
October	66	23	44	38	2.9	9.9	8.9	7.4
November	56	63	30	28	1.9	−2.4	−0.3	0.1
December	17	27	19	212	−8.0	−4.8	−3.1	−4.4
May–October	324	376	294	294	13.7	13.5	14.4	13.8
January–December	598	606	460	465	6.4	6.3	6.9	6.2

sand, 500 g kg^{-1} silt, and 250 g kg^{-1} clay at the 0–15 cm depth. Previous treatments (2004–2008) at the site included three fallow management practices for weed control (sheep grazing, tillage, and herbicide application) as the main plot and three cropping sequences (continuous spring wheat [CSW], spring wheat-fallow, and winter wheat-fallow) as the split-plot variable. For this experiment, the same fallow management practices were continued as the main plots and CSW as one of the cropping sequence split plot treatment. The other split plot cropping sequence (spring wheat-fallow and winter wheat-fallow) treatments were replaced by CA and W-P/B-F. As a result of the treatment history, SOC content at 0–120 cm varied in 2008 from 183 Mg C ha^{-1} in CHEM with CSW to 222 Mg C ha^{-1} in MECH with CSW (Sainju et al., 2010). Similarly, STN content at 0–120 cm varied from 19.5 Mg N ha^{-1} in MECH with spring wheat-fallow to 24.2 Mg N ha^{-1} in GRAZ with CSW (Sainju et al., 2010). These values were used as covariates for analysis for SOC and STN data collected from 2009 to 2011 to eliminate prior years' management effects.

The GRAZ treatment consisted of grazing with a group of western white-faced sheep at a stocking rate of 29–153 sheep day^{-1} ha^{-1}. Sheep were grazed before crop planting in the early spring and after harvest in the fall in CSW. In W-P/B-F, sheep were grazed during the summer fallow and after crop harvest in the fall. In CA, grazing occurred only after crop harvest in the fall. Grazing ended when about 47 kg ha^{-1} or less of crop residue and weeds remained in the plot. The amount of residue left at the soil surface after grazing was determined by collecting residues from five 900 m^2 areas within the plot, washing with water to remove soil particles, oven drying at 60 °C for 3 d, and weighing. The CHEM treatment was imposed by applying post emergence herbicide {glyphosate [*N*-(phosphonomethyl)-glycin] and dimethylamine salt of dicamba (3,6-dichloro-o-anisic acid)} before planting and after harvest for weed control. The MECH treatment consisted of tilling plots with Flexicoil harrow (John Deere 100, Kennedy, MN) to a depth of 15 cm during fallow to control weeds as needed and for seedbed preparation. Treatments were laid out in split-plot arrangement in a randomized complete block with three replications. Each phase of the cropping sequence was present every year. The size of the main plot was 91.4 m × 76.0 m and split plot 91.4 m × 15.2 m.

2.2. Crop management

Nitrogen fertilizer as urea (45% N) was broadcast to spring wheat and pea/barley hay before planting in mid-May, 2009 to 2011. While N fertilizer was left at the soil surface in GRAZ and CHEM treatments, it was incorporated to a depth of 15 cm using tillage in the MECH treatment. Nitrogen fertilization rates to spring wheat were 202 kg N ha^{-1} in CSW and 252 kg N ha^{-1} in W-P/B-F. Nitrogen rate to pea/barley hay in W-P/B-F was 134 kg N ha^{-1}. These rates were based on yield goals of 3.9 and 4.8 Mg ha^{-1} for spring wheat grain in CSW and W-P/B-F, respectively, and 8.9 Mg ha^{-1} for pea/barley hay in W-P/B-F. Nitrogen rates were adjusted to soil NO_3-N content to a depth of 60 cm measured after grain and hay harvest in the fall of the previous year so that desired N rates included both soil and fertilizer N. This was done to include soil residual N so that the concentration of N in the fertilization rates does not exceed the desired amount. No N fertilizer was applied to alfalfa. Since the soil contained high levels of extractable P and K (Sainju et al., 2011), no P and K fertilizers were applied.

Immediately after fertilization, spring wheat (cultivar McNeal, Foundation Seed, Montana State University, Bozeman, MT) was planted at 90 kg ha^{-1} in CSW and W-P/B-F treatments using a drill equipped with double disc openers spaced 30 cm apart. Using the same equipment, barley hay (cultivar Haybet, Montana State University Stock, Bozeman, MT) was planted at 1.6 million seeds ha^{-1} and Austrian winter pea hay (cultivar Arvika, Circle S Seed, Logan, UT) at 0.8 million seeds ha^{-1} in W-P/B-F. Alfalfa (cultivar Haygrazer, Browning Brothers Seed, Mosby, MT) was planted at 9 kg ha^{-1} with a JD 750 drill at a row spacing of 20 cm.

In September, total crop biomass (grains, stems, and leaves in spring wheat and stems and leaves in pea/barley hay and alfalfa) was collected 2 d before grain and hay harvest from two 0.5 m^2 areas per plot. Biomass samples were oven dried at 60 °C for 3 d and weighed for dry matter yield determination. Spring wheat grain yield (oven-dried basis) was determined from an area of 1389 m^2 using a combine harvester after oven-drying a subsample for 60 °C for 3 d. Spring wheat biomass (stems and leaves) was determined by deducting grain yield from total biomass. Subsamples of spring wheat grain and biomass and pea/barley and alfalfa biomass were ground to 1 mm for C and N analysis. Total C and N concentrations in plant samples were determined by using the high combustion C and N analyzer (LECO, St. Joseph, MI). Carbon and N contents in grain and biomass were calculated by multiplying their yields by C and N concentrations. Biomass of spring wheat after grain harvest and those of alfalfa and pea/barley were removed from the soil for hay with a self-propelled mower-conditioner and square baler in CHEM and MECH treatments. In the GRAZ treatment, sheep were allowed to graze over spring wheat, pea/barley, and alfalfa biomass. Because of the transitional year, grain and biomass yields and C and N contents were not measured in 2009, although all crop residues were removed from the soil.

2.3. Soil sampling and analysis

Except for the CA treatment in 2009, soil samples were collected at the 0–120 cm depth from five places in central rows of each plot using a hydraulic probe (5 cm inside diameter) in all cropping sequences in October (a month after crop harvest) of each year. Soil cores were divided into 0–5, 5–15, 15–30, 30–60, 60–90, and 90–120 cm depth intervals. A portion of the sample was used to determine the bulk density by dividing the weight of the oven-dried soil at 105 °C by the volume of the core. The remainder of each sample was air-dried and ground to pass a 2-mm sieve. The SOC and STN concentrations in soil samples were determined by using a high combustion C and N analyzer as for plant samples above after grinding the sample to 0.5 mm and treating with 5% H_2SO_3 to remove inorganic C (Nelson and Sommers, 1996). The NH_4-N and NO_3-N concentrations in soil samples were determined by extracting samples with 2 mole L^{-1}KCl for 1 h and analyzing the extract colorimetrically with an autoanalyzer (Lachat Instruments, Loveland, CO), where NH_4-N was determined using the indophenol blue reaction and NO_3-N was reduced to NO_2-N using Cd reduction and quantified using a modified Griess-Ilosvay method (Mulvaney, 1996).

The SOC, STN, NH_4-N, and NO_3-N contents (Mg or kg C and N ha^{-1}) at various depths were calculated by multiplying their concentrations (g or mg C kg^{-1}) by the bulk density and the thickness of the soil layer. Since the bulk density at all depths was not significantly influenced by treatments and years, values of 1.20, 1.34, 1.61, 1.61, 1.53, and 1.46 Mg m^{-3} at 0–5, 5–15, 15–30, 30–60, 60–90, and 90–120 cm, respectively, averaged across treatments and years, were used to convert concentrations of soil C and N into contents. Total contents at 0–120 cm were determined by summing the contents from individual depths.

2.4. Data analysis

Data for crop parameters were analyzed by using the SAS-MIXED model, after considering year as a repeated measure variable (Littell et al., 2006). Fallow management

Table 2
Effects of fallow management and cropping sequence on spring wheat grain and biomass yields in 2010 and 2011.

Cropping sequence[a]	Year	Grain yield ($Mg\,ha^{-1}$)	Biomass yield ($Mg\,ha^{-1}$)	C content ($Mg\,C\,ha^{-1}$)		N content ($Mg\,N\,ha^{-1}$)	
				Grain	Biomass	Grain	Biomass
CSW		2.31b[b]	5.06b	0.98b	2.15b	31.6b	68.5b
W-P/B-F		3.55a	7.37a	1.51a	3.14a	48.2a	100.2a
	2010	3.71a	6.87a	1.58a	2.94a	52.8a	98.3a
	2011	2.14b	5.56b	0.91b	2.36b	27.1b	70.4b
Significance							
Fallow management (FM)		NS	NS	NS	NS	NS	NS
Cropping sequence (CS)		**	**	*	**	*	**
FM × CS		NS	NS	NS	NS	NS	NS
Year (Y)		*	*	*	*	**	**
FM × Y		NS	NS	NS	NS	NS	NS
CS × Y		NS	NS	NS	NS	NS	NS
FM × CS × Y		NS	NS	NS	NS	NS	NS

NS, not significant.
[a] Cropping sequences are CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow.
[b] Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.
* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.

was considered as the main plot treatment and a fixed effect, cropping sequence as the split plot treatment and another fixed effect, and replication and replication × fallow management interaction as random effects. Data for soil parameters at multiple depths were analyzed by using the Analysis of Covariance in the SAS-MIXED model after values in 2008 were considered as covariates and treatments and year as variables similar to crop parameters, as described above. Since W-P/B-F had three cropping phases (spring wheat, pea/barley hay, and fallow) with each phase of the cropping sequence occurring in every year, data for soil parameters were averaged across phases within the sequence, and the average value was used for a cropping sequence for analysis. When 2008 covariate parameters were not significant, such as for soil NH_4-N and NO_3-N contents, data from 2009 to 2011 were analyzed using the SAS-MIXED model without using covariate analysis. Means were separated by using the least square means test when treatments and interactions were significant (Littell et al., 2006). Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

3. Results and discussion

3.1. Precipitation and air temperature

Monthly total precipitation highly varied (Table 1). Precipitation was greater in May and June, the active crop growing season, but lower in July in 2010 and 2011 than during the same periods in 2009 and the 113-yr average (Table 1). Precipitation in August and September was greater in 2010 than in other years. Overall, growing season (May-October) precipitation accounted for 54 to 64% of the total annual precipitation. Both growing season and total annual precipitation were greater in 2010 than in other years.

Monthly average air temperature in May and June was lower in 2010 and 2011 than in the 113-yr average (Table 1). Air temperature from July to September was greater in 2011 than in other years. Both growing season and annual average temperature were greater in 2011 than in other years. Variations in precipitation and air temperature among growing seasons and years significantly influenced crop yields and soil C and N levels, as described below. A severe hailstorm after harvest of spring wheat and pea/barley hay in September 2010 damaged alfalfa that resulted in no harvest of that crop.

3.2. Crop yields and carbon and nitrogen contents

Spring wheat grain and biomass yields and C and N contents varied among cropping sequences and years (Table 2). Grain and biomass yields and C and N contents were greater with W-P/B-F than with CSW. Conservation of soil water during fallow and lower water requirement for pea/barley hay than for spring wheat as a result of early harvest probably increased grain and biomass yields and C and N contents with W-P/B-F compared to CSW. Several researchers (Aase and Pikul, 1995; Lenssen et al., 2007; Sainju et al., 2009b) have found greater spring wheat grain and biomass yields following fallow than following spring wheat due to soil water accumulation during fallow. Lenssen et al. (2010) have reported that soil water and NO_3-N contents were greater in durum following fallow and pea/barley hay than following durum. Spring wheat grain and biomass yields and C and N contents were also greater in 2010 than in 2011, likely due to higher growing season precipitation (Table 1). Fallow management and its interaction with cropping sequence and year were not significant on spring wheat grain and biomass yields and C and N contents. Several researchers (Snyder et al., 2007; Sainju et al., 2011) have also found no differences in spring wheat grain and biomass yields in sheep-grazed and non-grazed treatments in southwestern Montana, USA.

Because of the severe hailstorm damage, alfalfa forage was not harvested and no measurements were made in CA in 2010. In 2011, alfalfa biomass and C content with CA were similar to pea/barley hay biomass and C content with W-P/B-F, but N content was greater in alfalfa than in pea/barley hay (Table 3). Because of the higher tissue N concentration, alfalfa had higher N content than pea/barley hay, a case similar to that reported by Sainju and Lenssen (2011). Pea/barley hay biomass and C content in W-P/B-F were also similar in 2010 and 2011 but biomass N content was greater in 2010 than in 2011 due to higher N concentration.

Annualized spring wheat grain and hay yields were lower with W-P/B-F than with CSW and CA because spring wheat and alfalfa were grown with CSW and CA every year in contrast to two out of there years grown with W-P/B-F. This resulted in significant differences in the annualized amounts of C and N returned to the soil through leftover residue after the aboveground biomass harvest and from belowground residue. Furthermore, residue placement in the soil due to tillage and consumption due to sheep grazing caused significant differences in soil C and N levels, as described below.

Table 3
Effects of fallow management and cropping sequence on alfalfa and pea/barley hay in 2010 and 2011.

Cropping sequence[a]	Biomass yield (Mg ha^{-1})		Biomass C content (Mg C ha^{-1})		Biomass N content (Mg N ha^{-1})	
	2010	2011	2010	2011	2010	2011
CA (alfalfa)	ND[b]	7.07a[c]	ND	3.1a	ND	182.1a
W-P/B-F (pea/barley hay)	6.56	7.01a	2.8	2.9a	100.8	86.8b
Significance						
Fallow management (FM)	–[d]	NS	–	NS	–	NS
Cropping sequence (CS)	–	***	–	***	–	***
FM × CS	–	NS	–	NS	–	NS

NS, not significant.

[a] Cropping sequences are CA, continuous alfalfa; and W-P/B-F, spring wheat-pea/barley hay-fallow.

[b] Not determined due to hailstorm damage.

[c] Numbers followed by different letters within a column are significantly different at $P \le 0.05$ by the least square means test.

[d] Not analyzed because of the lack of alfalfa data in 2010.

*** Significant at $P \le 0.001$.

3.3. Soil organic carbon

Eliminating the variability due to 2008 SOC levels using the covariate analysis, SOC from 2009 to 2011 varied with cropping sequences at 15–30, 0–30, and 0–60 cm depths and with years at all depths, except at 0–5 and 60–90 cm (Table 4). Significant interaction occurred for cropping sequence × fallow management at 5–15, 30–60, 0–15, and 0–60 cm. Fallow management had no effect on SOC at all depths.

The SOC at 5–15 and 0–15 cm, averaged across years, was greater with W-P/B-F than with CA in GRAZ, and was greater with CSW and W-P/B-F than with CA in MECH (Table 4). At 30–60 cm, SOC was also greater with W-P/B-F than with CA and CSW in GRAZ, but was greater with CA than with CSW in MECH. At 0–60 cm, SOC was greater with CSW and W-P/B-F than with CA in GRAZ. Since aboveground biomass of spring wheat after grain harvest and forages were removed by sheep during grazing, higher SOC with W-P/B-F and CSW than with CA in GRAZ could be a result of differences in duration of grazing in cropping sequence treatments. In GRAZ, sheep grazed before crop planting in the spring, after harvest in the fall, and during summer fallow with W-P/B-F; before planting and after harvest with CSW; and during fall with CA. It could be possible that the greater amount of C input returned to the soil through sheep feces and urine due to longer duration of grazing increased SOC with W-P/B-F and CSW than with CA in GRAZ. Moderate animal grazing can increase SOC level compared to no grazing, but heavy grazing can reduce the level (Franzluebbers and Stuedemann, 2008; Li et al., 2008). Similarly, greater SOC at 5–15 and 0–15 cm with CSW and W-P/B-F than with CA in MECH was probably due to the incorporation of left-over crop residue after harvest into the soil due to tillage conducted to a depth of 15 cm (Schomberg and Jones, 1999), since aboveground biomass was harvested for hay. In MECH, plots under annual crops, such as spring wheat and pea/barley hay, were tilled two to three times a year to control weeds in contrast to plots under perennial crops, such as alfalfa, which were tilled only once at the time of plant establishment. In contrast, greater SOC at 30–60 cm with CA than with CSW in MECH was probably due to greater root biomass of alfalfa than annual crops at deeper layers (Sainju et al., 2011).

Table 4
Effects of fallow management and cropping sequence on soil organic C (SOC) content at the 0–120 cm depth from 2009 to 2011.

Fallow management (FM)[a]	Cropping sequence (CS)[b]	Year (Y)	SOC content (Mg C ha^{-1}) at the soil depth										
			0–5 cm	5–15 cm	15–30 cm	30–60 cm	60–90 cm	90–120 cm	0–15 cm	0–30 cm	0–60 cm	0–90 cm	0–120 cm
CHEM	CA		16.2	33.7	37.0	39.1	28.4	21.3	49.9	86.9	126.0	154.3	175.6
	CSW		16.6	36.8	33.8	41.1	45.6	38.6	53.1	87.2	129.3	174.4	216.1
	W-P/B-F		16.5	33.8	37.5	38.7	36.8	34.9	49.7	88.1	127.0	164.4	201.7
GRAZ	CA		15.1	29.1	19.6	23.0	49.6	28.7	44.2	63.9	86.8	136.4	165.1
	CSW		16.4	30.8	27.8	33.2	49.2	28.6	47.7	75.8	108.3	159.6	188.5
	W-P/B-F		16.6	34.7	37.6	39.8	37.1	31.9	51.3	88.7	128.7	165.4	196.9
MECH	CA		15.9	29.4	29.8	45.8	34.6	29.8	45.4	74.7	120.5	155.1	184.9
	CSW		15.9	33.7	34.9	37.5	37.0	31.3	49.1	83.9	121.2	159.6	188.3
	W-P/B-F		15.8	34.3	36.2	40.7	35.7	34.9	50.4	85.9	126.5	162.2	192.2
LSD (0.05)			NS	3.5	NS	6.6	NS	NS	3.7	NS	18.8	NS	NS
Means													
	CA		15.7a[c]	30.8a	28.6c	36.0a	37.5b	26.6a	46.5a	75.1c	111.1c	148.6a	175.2a
	CSW		16.3a	33.8a	32.2b	37.2a	43.9a	32.8a	50.0a	82.3b	119.6b	163.6a	196.7a
	W-P/B-F		16.3a	34.3a	37.1a	39.7a	36.5b	32.5a	50.5a	87.5a	127.4a	164.0a	197.0a
		2009	16.6a	36.7a	40.8a	43.7a	41.6a	38.7a	53.2a	94.0a	137.7a	179.3a	218.0a
		2010	16.6a	33.0b	31.4b	37.0b	40.5a	28.0b	49.7b	81.2b	118.0b	158.5b	185.9b
		2011	16.4a	32.2b	32.9b	36.0b	35.4a	29.5b	48.8b	81.7b	117.5b	152.8b	181.7b
Significance													
CS			NS	NS	*	NS	NS	NS	NS	*	*	NS	NS
FM			NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM			NS	*	NS	*	NS	NS	*	NS	**	NS	NS
Y			NS	**	***	*	NS	*	**	***	***	***	***
CS × Y			NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
FM × Y			NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM × Y			NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
SOC (2008)[d]			*	***	***	NS	*	NS	***	***	***	**	NS

NS, not significant.

[a] Fallow management practices are CHEM, weed controlled by herbicide application; GRAZ, weed controlled by sheep grazing; and MECH, weed controlled by tillage.

[b] Cropping sequences are CA, continuous alfalfa; CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow.

[c] Numbers followed by different letters within a column in a set are significantly different at $P \le 0.05$ by the least square means test.

[d] SOC content in 2008 used as a covariate for data analysis.

* Significant at $P \le 0.05$.

** Significant at $P \le 0.01$.

*** Significant at $P \le 0.001$.

Table 5

Effects of fallow management and cropping sequence on soil total N (STN) content at the 0–120 cm depth from 2009 to 2011.

Fallow management (FM)[a]	Cropping sequence (CS)[b]	Year (Y)	STN content (Mg N ha^{-1}) at the soil depth										
			0–5 cm	5–15 cm	15–30 cm	30–60 cm	60–90 cm	90–120 cm	0–15 cm	0–30 cm	0–60 cm	0–90 cm	0–120 cm
CHEM	CA		1.67	3.07	3.45	3.88	2.83	2.10	4.72	8.15	12.03	14.86	16.97
	CSW		1.67	3.32	3.69	3.92	2.69	2.15	4.98	8.62	12.72	15.48	17.63
	W-P/B-F		1.66	3.13	3.99	4.28	2.76	2.22	4.86	8.77	13.13	15.88	18.12
GRAZ	CA		1.45	2.67	2.67	3.25	2.33	2.12	4.12	6.80	10.08	12.40	14.53
	CSW		1.60	2.76	3.11	3.95	3.02	2.21	4.59	7.40	10.99	13.91	16.15
	W-P/B-F		1.55	3.17	3.74	4.03	2.83	2.19	4.60	8.42	12.46	15.26	17.44
MECH	CA		1.52	2.77	3.07	3.55	2.60	1.98	4.28	7.33	10.88	13.48	15.47
	CSW		1.60	3.15	3.55	3.93	2.81	2.26	4.72	8.26	12.18	14.97	17.17
	W-P/B-F		1.53	3.13	3.75	4.04	2.93	2.40	4.64	8.49	12.51	15.50	17.75
LSD (0.05)			NS	0.37	NS	NS	NS	NS	NS	NS	NS	NS	NS
Means													
	CA		1.54a[c]	2.83a	3.06c	3.56a	2.59a	2.07a	4.37a	7.42c	11.00c	13.58c	15.71c
	CSW		1.62a	3.08a	3.45b	3.93a	2.85a	2.21a	4.76a	8.09b	11.96b	14.79b	17.00b
	W-P/B-F		1.58a	3.14a	3.83a	4.12a	2.84a	2.22a	4.70a	8.56a	12.70a	15.54a	17.77a
		2009	1.63a	3.43a	4.32a	4.53a	3.24a	2.39a	5.05a	9.36a	13.89a	17.13a	19.53a
		2010	1.59a	3.08b	3.41b	3.93b	2.69b	2.16b	4.68b	8.09b	12.00b	14.67b	16.84b
		2011	1.55a	2.85b	3.14b	3.46c	2.51b	2.04b	4.39c	7.53c	10.96c	13.46c	15.51c
Significance													
CS			NS	NS	**	NS	NS	NS	NS	**	**	*	*
FM			NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM			NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
Y			NS	***	***	***	***	***	**	***	**	***	***
CS × Y			NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
FM × Y			NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM × Y			NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
STN (2008)[d]			*	***	*	NS	NS	NS	***	***	***	**	***

NS, not significant.

[a] Fallow management practices are CHEM, weed controlled by herbicide application; GRAZ, weed controlled by sheep grazing; and MECH, weed controlled by tillage.

[b] Cropping sequences are CA, continuous alfalfa; CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow.

[c] Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

[d] STN content at 2008 used as a covariate for data analysis.

[*] Significant at $P \leq 0.05$.

[**] Significant at $P \leq 0.01$.

[***] Significant at $P \leq 0.001$.

Averaged across fallow management practices and years, SOC at 15–30, 0–30, and 0–60 cm was in the order: W-P/B-F > CSW > CA (Table 4). At 60–90 cm, SOC was greater with CSW than with CA and W-P/B-F. Since aboveground biomass was removed in all treatments, it is likely that summer fallow increased soil water content in the previous year and consequently root biomass in the succeeding year, which enriched SOC at 15–30 cm with W-P/B-F than with CSW and CA. The reasons for greater SOC at 60–90 cm with CSW than with CA and W-P/B-F were not known. Averaged across treatments, SOC declined from 2009 to 2011 at all depths, except at 0–5 and 60–90 cm. Removal of aboveground biomass of spring wheat and forages for hay and those from sheep grazing probably reduced SOC from 2009 to 2011. Similar reduction in SOC levels from 2004 to 2007, regardless of treatments, was observed previously in this experiment (Sainju et al., 2010). Removal of crop residue can reduce SOC level compared to no removal (Halvorson et al., 2002; Sainju et al., 2009a). Treatments did not affect SOC at 0–120 cm. Management practices effect on SOC level typically occur at individual depth layers, especially at surface layers, rather than the whole soil profile (Kravchenko and Robertson, 2011; Syswerda et al., 2011).

3.4. Soil total nitrogen

Eliminating the variability from 2008 STN levels, similar to SOC, STN from 2009 to 2011varied among cropping sequences at 15–30, 0–30, 0–60, 0–90, and 0–120 cm, and among years at all depths, except at 0–5 cm (Table 5). Interaction was significant for cropping sequence × fallow management at 5–15 cm. Fallow management did not influence STN at all depths.

The STN at 5–15 cm was greater with W-P/B-F than with CA and CSW in GRAZ, and greater with CSW than with CA in MECH (Table 5). As with SOC, longer duration of sheep grazing, resulting in greater return of N input through feces and urine, probably increased STN at 5–15 cm with W-P/B-F compared to CSW and CA in GRAZ. Similarly, residue incorporation to a greater depth due to increased frequency of tillage likely increased STN at 5–15 cm with CSW compared to CA in MECH.

Averaged across fallow management practices, STN at 15–30, 0–30, 0–60, 0–90, and 0–120 cm was in the order: W-P/B-F > CSW > CA (Table 5). Increased root biomass due to higher soil water conservation during the summer fallow in the previous year, probably increased STN with W-P/B-F compared to CSW and CA, a case similar to that observed for SOC. Similarly, like SOC, STN at almost all depths declined from 2009 to 2011, regardless of treatments, probably due to aboveground biomass removal for hay and from sheep grazing.

3.5. Soil ammonium-nitrogen

In contrast to SOC and STN, covariate analysis revealed that 2008 NH_4-N levels had no effect on the levels from 2009 to 2011. With the removal of 2008 levels for data analysis, NH_4-N content from 2009 to 2011 was not affected by treatments, but varied among years at all depths, except at 15–30, 30–60, 60–90, and 90–120 cm (Table 6). Significant interactions occurred for cropping

Table 6
Effects of fallow management and cropping sequence on soil NH_4-N content at the 0–120 cm depth from 2009 to 2011.

Year	NH_4-N content (kg N ha^{-1}) at the soil depth										
	0–5 cm	5–15 cm	15–30 cm	30–60 cm	60–90 cm	90–120 cm	0–15 cm	0–30 cm	0–60 cm	0–90 cm	0–120 cm
2009	3.08b[a]	7.53b	11.59a	21.58a	18.67a	19.02a	10.61b	22.20b	43.77a	62.44a	81.46a
2010	4.56a	9.09a	12.25a	20.84a	18.96a	20.02a	13.66a	25.91a	46.74a	65.71a	85.74a
2011	3.19b	5.62c	10.29a	18.73a	17.55a	18.90a	8.81c	19.10c	37.83b	55.38b	74.28b
Significance											
Cropping sequence (CS)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Fallow management (FM)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year (Y)	[**]	[***]	NS	NS	NS	NS	[***]	[**]	[*]	[*]	[*]
CS × Y	[*]	NS	NS	NS	NS	[*]	NS	NS	NS	NS	NS
FM × Y	NS	[*]	NS	NS	NS	NS	[*]	[*]	NS	NS	NS
CS × FM × Y	[*]	NS	NS	[*]	[*]	NS	[*]	NS	[*]	[*]	[*]

NS, not significant.

[a] Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least square means test.

[*] Significant at $P \leq 0.05$.

[**] Significant at $P \leq 0.01$.

[***] Significant at $P \leq 0.001$.

sequence × year at 0–5 and 90–120 cm, fallow management × year at 5–15, 0–15, and 0–30 cm, and cropping sequence × fallow management × year at 0–5, 30–60, 60–90, 0–15, 0–60, 0–90, and 0–120 cm.

In 2009, NH_4-N content at 0–5 and 0–15 cm was greater with CSW than with W-P/B-F in MECH (Table 7). In 2010, NH_4-N content at 0–5, 30–60, 0–15, 0–60, 0–90, and 0–120 cm was greater with CA than with CSW and W-P/B-F in GRAZ. In 2011, NH_4-N content at 30–60, 0–60, and 0–90 cm was greater with CA than with CSW and W-P/B-F in CHEM. While greater NH_4-N content with CSW than with W-P/B-F in MECH was probably due to higher N fertilization rate to spring wheat than to pea/barley hay, increased NH_4-N content with CA than with CSW and W-P/B-F in GRAZ and CHEM was probably a result of enhanced N fixation by alfalfa. Alfalfa crown and roots can supply up to 115 kg N ha^{-1}, greater than that supplied by aboveground biomass (Rasse et al., 1999). Greater NH_4-N content at almost all depths in 2010 than in 2009 and 2011 (Table 6) was probably due to higher precipitation (Table 1) that increased N mineralization.

3.6. Soil nitrate-nitrogen

Similar to NH_4-N content, covariate analysis showed that NO_3-N contents from 2009 to 2011 were not influenced by the 2008

Table 7
Interaction effect of fallow management, cropping sequence, and year on soil NH_4-N content at the 0–120 cm depth.

Year	Fallow management[a]	Cropping sequence[b]	NH_4-N content (kg N ha^{-1}) at the soil depth										
			0–5 cm	5–15 cm	15–30 cm	30–60 cm	60–90 cm	90–120 cm	0–15 cm	0–30 cm	0–60 cm	0–90 cm	0–120 cm
2009	CHEM	CA	ND[c]	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		CSW	5.54	5.58	9.28	17.43	15.74	22.82	8.26	17.54	34.98	50.72	73.54
		W-P/B-F	3.24	6.34	11.59	19.77	17.03	15.69	9.58	21.16	40.94	57.97	73.65
	GRAZ	CA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		CSW	3.37	6.94	10.62	22.85	19.54	18.52	10.08	20.70	43.54	63.08	81.59
		W-P/B-F	3.10	6.54	12.38	22.41	21.33	20.80	9.64	22.02	44.42	65.75	86.55
	MECH	CA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		CSW	7.54	16.42	10.56	18.38	17.63	16.32	18.92	29.48	47.87	65.50	81.82
		W-P/B-F	3.22	7.59	12.22	24.57	18.69	20.38	10.81	23.03	47.60	66.29	86.67
2010	CHEM	CA	3.58	9.60	12.04	23.07	17.33	25.04	13.18	25.22	48.29	65.63	90.67
		CSW	2.62	6.06	9.48	14.40	15.48	22.18	9.43	18.91	33.31	48.79	70.97
		W-P/B-F	2.93	10.14	10.71	18.61	11.99	13.73	13.07	23.78	42.39	54.39	68.12
	GRAZ	CA	6.80	12.64	19.13	36.16	43.50	39.42	19.43	38.56	74.72	118.21	157.63
		CSW	3.33	11.26	9.00	15.39	15.84	10.69	18.81	27.81	43.20	59.04	69.72
		W-P/B-F	3.43	7.45	13.80	16.16	18.73	18.50	10.88	24.68	40.84	59.57	78.07
	MECH	CA	2.70	8.31	10.34	16.79	12.70	15.44	13.85	24.18	40.98	53.68	69.12
		CSW	2.50	7.89	13.66	25.87	17.50	16.91	12.53	26.19	52.06	69.57	86.48
		W-P/B-F	3.19	8.53	12.12	21.10	17.60	18.36	11.72	23.84	44.94	62.54	80.90
2011	CHEM	CA	3.67	7.62	19.27	35.76	16.52	16.41	11.28	30.56	66.31	82.84	99.25
		CSW	2.67	5.90	10.29	19.78	15.74	32.00	9.24	19.53	39.31	55.06	87.06
		W-P/B-F	2.61	6.11	9.77	15.24	14.45	17.78	8.73	18.50	33.74	48.19	65.97
	GRAZ	CA	3.54	5.59	8.21	14.10	15.99	16.34	9.13	17.34	31.44	47.43	63.77
		CSW	3.14	5.57	11.16	19.29	22.64	20.97	8.28	19.43	38.72	61.36	82.33
		W-P/B-F	5.78	5.78	9.94	19.93	19.32	16.80	11.55	21.50	41.43	60.75	77.55
	MECH	CA	4.64	5.00	8.25	15.80	21.33	15.94	7.62	15.88	31.67	53.00	68.94
		CSW	2.09	4.32	7.85	13.30	14.78	13.36	6.41	14.26	27.56	42.34	55.69
		W-P/B-F	2.33	4.71	7.91	15.37	17.15	20.49	7.04	14.95	30.32	47.46	67.95
	LSD (0.05)		3.23	NS	NS	13.4	16.7	NS	6.1	NS	27.6	35.4	44.8

[a] Fallow management practices are CHEM, weed controlled by herbicide application; GRAZ, weed controlled by sheep grazing; and MECH, weed controlled with by tillage.

[b] Cropping sequences are CA, continuous alfalfa; CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow.

[c] Not determined.

Table 8
Effects of fallow management and cropping sequence on soil NO_3-N content at the 0–120 cm depth from 2009 to 2011.

Year	Cropping sequence[a]	NO_3-N content (kg N ha^{-1}) at the soil depth										
		0–5 cm	5–15 cm	15–30 cm	30–60 cm	60–90 cm	90–120 cm	0–15 cm	0–30 cm	0–60 cm	0–90 cm	0–120 cm
2009	CA	ND[b]	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	CSW	3.8	21.0	34.9	17.4	20.3	54.2	24.8	59.7	76.8	97.1	151.3
	W-P/B-F	7.9	25.7	38.5	22.6	23.4	30.1	33.6	72.1	94.6	118.0	148.1
2010	CA	5.5	11.9	11.3	14.0	10.0	6.6	17.4	28.7	42.7	52.7	59.3
	CSW	10.9	26.8	34.5	26.4	14.8	14.4	37.7	72.3	98.7	113.5	127.9
	W-P/B-F	10.5	25.5	27.8	20.3	18.5	22.9	36.0	63.8	84.0	102.5	125.3
2011	CA	20.2	5.6	6.5	6.7	7.4	8.0	25.8	32.3	39.0	46.4	54.4
	CSW	22.1	15.6	17.5	12.3	22.0	31.7	37.8	55.2	67.5	89.5	121.2
	W-P/B-F	19.7	14.1	12.5	12.7	17.8	26.6	33.8	46.3	59.1	76.9	103.4
LSD (0.05)		NS	NS	NS	NS	NS	12.1	NS	NS	NS	NS	NS
Means												
	CA	12.8a[c]	8.7b	8.9b	10.3b	8.7b	7.3b	21.6b	30.5b	40.8b	49.6 b	56.9 b
	CSW	12.2a	21.2a	29.0a	18.6a	19.0a	33.5a	33.4a	62.4a	81.0a	100.0a	133.5a
	W-P/B-F	12.7a	21.8a	26.3a	18.5a	19.9a	26.5a	34.5a	60.7a	79.2a	99.1a	125.6a
2009		6.8b	24.5a	37.6a	21.2a	22.6a	36.1a	31.4a	69.8a	90.2a	112.7a	148.9 a
2010		9.6b	23.0a	25.8b	20.2a	16.0a	17.9b	32.6a	58.5a	78.7ab	94.7a	112.7b
2011		20.3a	12.7b	12.3c	11.4b	16.6a	23.9a	33.0a	45.3a	56.7b	73.3a	97.2 b
Significance												
Cropping sequence (CS)		NS	***	**	*	*	***	*	**	**	**	***
Fallow management (FM)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year (Y)		***	**	***	**	NS	***	NS	NS	*	NS	*
CS × Y		NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
FM × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS, not significant.

[a] Cropping sequences are CA, continuous alfalfa; CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow.

[b] Not determined.

[c] Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

* Significant at $P \leq 0.05$.

** Significant at $P \leq 0.01$.

*** Significant at $P \leq 0.001$.

NO_3-N levels. Eliminating the 2008 NO_3-N data for analysis, NO_3-N content from 2009 to 2011 varied among cropping sequences at all depths, except at 0–5 cm (Table 8). Similarly, NO_3-N content varied among years at all depths, except at 60–90, 0–15, 0–30, and 0–90 cm. Interaction was significant for cropping sequence × year at 90–120 cm. Fallow management had no effect on NO_3-N content.

At 90–120 cm, NO_3-N content was greater with CSW than with W-P/B-F in 2009 (Table 8). In 2010, NO_3-N content was greater with W-P/B-F than with CA. In 2011, NO_3-N content was greater with CSW and W-P/B-F than with CA. Greater NO_3-N content with CSW and W-P/B-F than with CA was clearly related to the amount of N fertilizer applied to crops. While spring wheat received 202 kg N ha^{-1} with CSW and 252 kg N ha^{-1} with W-P/B-F and pea/barley hay received 134 kg N ha^{-1} with W-P/B-F, alfalfa with CA received no N fertilizer. Since crops are unable to remove 100% of the applied N (Hallberg et al., 1985; Errebhi et al., 1998), it is likely that greater NO_3-N content with CSW and W-P/B-F resulted from higher N rate to crops. When growing season precipitation was higher in 2010 (Table 1), W-P/B-F, however, accumulated somewhat greater NO_3-N level than CSW at the subsurface layer, probably due to higher N mineralization during the fallow period and/or lower N removal by pea/barley hay compared to spring wheat (Tables 2 and 3). Since no significant cropping sequence × year interaction occurred at 0–90 cm, it is possible that residual soil NO_3-N after crop harvest leached from upper layers and accumulated at the 90–120 cm layer where the interaction was significant.

Averaged across fallow management practices and years, NO_3-N content at all depths, except at 0–5 cm, was greater with CSW and W-P/B-F than with CA (Table 8). As stated above, lower NO_3-N content with CA was either due to the absence of N fertilization or to greater uptake of NO_3-N from the soil by alfalfa due to its higher root biomass than annual crops (Mathers et al., 1975; Power et al., 2001). Because of higher root biomass, alfalfa can reduce soil NO_3-N content and the potential for N leaching compared to annual crops (Sainju et al., 2011). With the termination of alfalfa, its residue, however, can supply a large amount of N to the soil and increase the potential for N leaching (Rasse et al., 1999; Kavdir et al., 2005).

Averaged across treatments, NO_3-N content increased at 0–5 cm but decreased at 5–15, 15–30, 30–60, and 0–120 cm from 2009 to 2011 (Table 8). At 90–120 cm, NO_3-N content was greater in 2009 than in 2010 and 2011. The increased NO_3-N level at the surface layer but decreased levels at subsurface layers from 2009 to 2011 probably indicate increased N mineralization at the surface layer, but increased N loss due to leaching and denitrification at subsurface layers with time. Except at 0–5 cm, reduction in NO_3-N content at all depths from 2009 to 2011 also could be a result of reduced N substrate availability, since STN content decreased from 2009 to 2011 (Table 5).

4. Conclusions

With proper grazing management, sheep grazing had beneficial effects in increasing soil C and N storage and maintaining crop yields by leaving enough crop residues to protect the soil from erosion. While all crop residues were removed as hay in tillage and herbicide application treatments, sheep grazing removed about

99% of the residue. Longer duration of sheep grazing during fallow periods, resulting in increased return of C and N inputs to the soil through feces and urine, or residue incorporation due to tillage increased soil C and N storage at the surface layer with W-P/B-F and CSW than with CA in grazing and tillage treatments. This was in contrast to our hypothesis that sheep grazing would increase soil C and N compared to tillage and herbicide application in CA and CSW. While increased N fertilization rates to spring wheat and pea/barley hay increased NH_4-N and NO_3-N contents with CSW and W-P/B-F, absence of N fertilization and/or increased N uptake by alfalfa reduced soil NO_3-N content with CA. As a result, alfalfa may reduce the potential for N leaching compared to spring wheat and pea/barley hay. Sheep grazing during fallow periods can be used to increase soil C and N storage, obtain farm C credit, and sustain crop yields compared to herbicide application for weed control, provided enough crop residue is left in the ground to increase C and N cycling and reduce soil erosion. The information can be useful for dryland growers using integrated crop and livestock systems in regions where sheep grazing during fallow periods is done to reduce feed cost and control weeds in croplands.

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