Nutr Cycl Agroecosyst (2014) 99:79–93
DOI 10.1007/s10705-014-9619-8

ORIGINAL ARTICLE

Particulate and active soil nitrogen fractions are reduced by sheep grazing in dryland cropping systems

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Received: 8 January 2014 / Accepted: 21 May 2014 / Published online: 31 May 2014

Abstract Sheep (*Ovis aries* L.) grazing, a cost-effective method of weed control compared to herbicide application and tillage, may influence N cycling by consuming crop residue and weeds and returning N through feces and urine to the soil. The objective of this experiment was to evaluate the effect of sheep grazing compared to tillage and herbicide application for weed control on soil particulate and active soil N fractions in dryland cropping systems. Our hypothesis was that sheep grazing used for weed control would increase particulate and active soil N fractions compared to tillage and herbicide application. Soil samples collected at the 0–30 cm depth from a Blackmore silt loam were analyzed for particulate organic N (PON), microbial biomass N (MBN), and potential N mineralization (PNM) under dryland cropping systems from 2009 to 2011 in southwestern Montana, USA. Treatments were three weed management practices [sheep grazing (grazing), herbicide application (chemical), and tillage (mechanical)] as the main plot and two cropping sequences [continuous spring wheat (*Triticum aestivum* L.; CSW) and spring wheat–pea (*Pisum sativum* L.)/barley (*Hordeum vulgare* L.) mixture hay–fallow; W–P/B–F] as the split-plot factor arranged in randomized complete block with three replications. The PON and MBN at 0–30 cm were greater in the chemical or mechanical than the grazing treatment with CSW. The PNM at 15–30 cm was greater in the chemical or mechanical than the grazing treatment in 2009 and 2011 and at 5–15 cm was greater with W–P/B–F than CSW in 2010. From 2009 to 2011, PON at 0–30 cm and PNM at 15–30 cm reduced from 2 to 580 kg N ha^{-1} $year^{-1}$ in the grazing and chemical treatments, but the rate varied from −400 to 2 kg N ha^{-1} $year^{-1}$ in the mechanical treatment. Lower amount of labile than nonlabile organic matter returned to the soil through feces and urine probably reduced soil active and coarse organic matter N fractions with sheep grazing compared to herbicide application and tillage for weed control. Reduction in the rate of decline in N fractions from 2009 to 2011 compared to the herbicide application treatment, however, suggests that sheep grazing may stabilize N fractions in the long-term if the intensity of grazing is reduced. Animal grazing may reduce soil N fractions in annual cropping systems in contrast to known increased fractions in perennial cropping systems.

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Keywords Dryland cropping systems · Labile nitrogen fractions · Nitrogen cycling · Sheep grazing · Weed management

Abbreviations

Chemical	Weed control by herbicide application
CSW	Continuous spring wheat
Grazing	Weed control by sheep grazing
MBN	Microbial biomass N
Mechanical	Weed control by tillage
PNM	Potential N mineralization
PON	Particulate organic N
STN	Soil total N
W–P/B–F	Spring wheat–pea/barley mixture hay–fallow

Introduction

Sustainability of farming systems using reduced inputs can be achieved by using the integrated crop-livestock system (Franzluebbers and Stuedemann 2003, 2008; Maughan et al. 2009). Nitrogen returned to the soil through feces and urine during animal grazing on crop and weed residues can increase N cycling and reduce N fertilization rates for succeeding crops (Abaye et al. 1997; Franzluebbers and Stuedemann 2003; Sainju et al. 2010). As a result, grazing can increase soil quality and crop yields compared to non-grazing (Franzluebbers and Stuedemann 2003; Maughan et al. 2009). Some of the other benefits of the integrated crop-livestock system are meat, milk, wool, and manure production and use of animals as draft power for tillage (Franzluebbers and Stuedemann 2003; Hatfield et al. 2007).

Sheep grazing during fallow periods (e.g. before crop planting, after grain harvest, and during summer fallow) is often used to control weeds and pests, reduce feed cost, and increase nutrient cycling in dryland cropping systems (Johnson et al. 1997; Hatfield et al. 2007). Alternate-year summer fallow is usually practiced to conserve soil water, release plant nutrients, control weeds, increase succeeding crop yields, and reduce the risk of crop failure (Aase and Pikul 2000). While tillage and herbicide application are effective in controlling weeds, they are also expensive, resulting in some of the highest variable costs for small grain production (Johnson et al. 1997). Tillage and fallow can expose soil to erosion and herbicide application can contaminate soil, water, and air, all of which can increase risks to human and animal health (Fenster 1997).

Tillage and fallow can also reduce soil quality and productivity by reducing soil organic matter and water storage efficiency and increasing saline seeps development (Tanaka and Aase 1987; Black and Bauer 1988). While intensive tillage increases the oxidation of soil organic matter (Schomberg and Jones 1999), fallowing reduces the amount of crop residue returned to the soil and increases soil temperature and water content which increase microbial activity (Aase and Pikul 2000; Halvorson et al. 2002). Traditional dryland farming practices using conventional tillage with wheat–fallow have resulted in reduced crop yields and soil organic matter in the northern Great Plains, USA (Aase and Pikul 2000; Halvorson et al. 2002; Sainju et al. 2009).

Management practices change soil total N (STN) slowly due to a large pool size and inherent spatial variability (Franzluebbers et al. 1995). The STN include greater proportion of nonlabile fractions of soil N (or soil organic N) that are resistant to change (Franzluebbers et al. 1995). As a result, measurement of STN alone does not reflect changes in soil productivity and N status (Franzluebbers et al. 1995; Bezdicek et al. 1996). Measurements of biologically active (labile) fractions of STN, such as microbial biomass N (MBN or N stored in the body of microorganisms) and potential N mineralization (PNM or N mineralization capacity) that change rapidly with time (e.g. within a growing season), can better reflect changes in soil quality and productivity that alter N dynamics due to immobilization-mineralization (Saffigna et al. 1989; Bremner and Van Kissel 1992). Particulate organic N (PON or N in coarse organic matter fraction) is an intermediate N fraction between active and slow fractions that also changes rapidly due to management practices (Cambardella and Elliott 1992) and can be a sensitive indicator of changes in soil organic matter (Franzluebbers and Stuedemann 2003). Compared to conventional management practices, conservation practices can increase both active and intermediate fractions of soil N better than slow fractions (Franzluebbers et al. 1995; Sainju et al. 2009). Animal grazing can increase soil particulate organic matter, soil microbial biomass, and N mineralization in perennial cropping systems (Franzluebbers and Stuedemann 2003; Frank and Groffman 1998), but can reduce their contents in annual cropping systems (Franzluebbers and Stuedemann 2008).

Quantifying particulate and biologically active soil N fractions is needed to measure the impact of management practices on soil N cycling and productivity. Little is known about the effect of sheep grazing on active and intermediate soil N fractions in dryland cropping systems. We hypothesized that sheep grazing for weed control in continuous spring wheat (CSW) would increase active and intermediate soil N fractions (PON, MBN, and PNM) compared to tillage and herbicide application on spring wheat–pea/barley mixture hay–fallow (W–P/B–F). Our objectives were to: (1) quantify the effects of weed management practices (sheep grazing, tillage, and herbicide application) and cropping sequences (CSW and W–P/B–F) on PON, MBN, and PNM from 2009 to 2011 in southwestern Montana, USA and (2) identify if sheep grazing for weed control is a viable option to increase N cycling in dryland cropping systems.

Materials and methods

Experimental description

The study was conducted from 2009 to 2011 at the Fort Ellis Research Center, Montana State University (45°40′N, 111°2′W; altitude 1,468 m), Bozeman, Montana, USA. Mean monthly air temperature ranges from −5.6 °C in January to 19 °C in July and the annual precipitation (113-year average) is 465 mm. The soil is a Blackmore silt loam (fine-silty, mixed, superactive, frigid Typic Argiustolls) with 250 g kg^{-1} sand, 500 g kg^{-1} silt, 250 g kg^{-1} clay, and 7.2 pH at the 0–15 cm depth. Previous treatments (2004–2008) at the site included three weed management practices (sheep grazing, tillage, and herbicide application) as the main plot and three cropping sequences (CSW, spring wheat–fallow, and winter wheat–fallow) as the split-plot variable. The CSW included only one crop phase (spring wheat) while spring wheat–fallow had two crop phases (spring wheat and fallow), with each phase occurring in every year. Similarly, winter wheat–fallow had two phases (winter wheat and fallow), with each phase occurring in every year. In 2009, the same weed management practices were continued as the main plot and CSW as one of the cropping sequence in the split plot treatment. In the other split-plot treatments, winter wheat phase of the winter wheat–fallow treatment was replaced by alfalfa (*Medicago sativa* L.). Its second phase (fallow) as well as spring wheat and fallow phases of the spring wheat–fallow treatment were replaced by three phases of pea/barley hay mixture, fallow, and spring wheat, respectively, in the W–P/B–F rotation where each phase appeared in every year. For this study, cropping sequences with only CSW and W–P/B–F were selected. As a result of the treatment history, STN content at 0–120 cm varied from 19.5 Mg N ha^{-1} in the mechanical treatment with spring wheat–fallow to 24.2 Mg N ha^{-1} in the grazing treatment with CSW in 2008 (Sainju et al. 2010). These values were used as covariates for data analysis to eliminate prior years' management effects on soil N fractions.

Detailed description of treatments and management practices used for crop production are shown in Table 1. Main-plot treatments were three weed management practices [chemical (weed control by herbicide application), grazing (weed control by sheep grazing), and mechanical (weed control by tillage)] and split-plot treatments were two cropping sequences (CSW and W–P/B–F) arranged in a randomized block design with three replications. The grazing treatment consisted of grazing with a group of western whitefaced sheep at a stocking rate of 29–153 sheep day^{-1} ha^{-1}. Sheep were grazed day and night before crop planting in the early spring and after harvest in the autumn in CSW. In addition to these periods, sheep were also grazed during the summer fallow period in W–P/B–F. Grazing ended when about ≤47 kg ha^{-1} 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 cm^2 areas within the plot, washing with water to remove soil particles, oven drying at 60 °C for 3 day, and weighing. The chemical treatment included application of post emergence herbicide {glyphosate [*N*-(phosphonomethyl)-glycin] and dimethylamine salt of dicamba (3,6-dichloro-*o*-anisic acid)} before planting, after crop harvest, and during summer fallow for weed control. The mechanical treatment consisted of tilling the plots before planting, during crop growth, after crop harvest, and during summer fallow with a Flexicoil harrow (John Deere 100, Kennedy, MN) to a depth of 15 cm to control weeds and for seedbed

Table 1 Description of management practices used for various treatments in the experiment from 2009 to 2011

Management	Chemical		Grazing		Mechanical	
	CSW	W–P/B–F	CSW	W–P/B–F	CSW	W–P/B–F
Tillage	None	None	None	None	Harrowing to a depth of 15 cm	Harrowing to a depth of 15 cm
Weed management	Herbicide application in the spring and autumn	Herbicide application in the spring, autumn, and summer fallow	Sheep grazing before planting in the spring and after crop harvest in the autumn	Sheep grazing before planting in the spring, after crop harvest in the autumn, and during summer fallow	Tillage in the spring, summer, and autumn	Tillage in the spring, summer, and autumn
N fertilization rate	202 kg N ha^{-1} for wheat	252 kg N ha^{-1} for wheat and 134 kg N ha^{-1} for pea/barley mixture hay	202 kg N ha^{-1} for wheat	252 kg N ha^{-1} for wheat and 134 kg N ha^{-1} for pea/barley mixture hay	202 kg N ha^{-1} for wheat	252 kg N ha^{-1} for wheat and 134 kg N ha^{-1} for pea/barley mixture hay
P and K fertilization	None	None	None	None	None	None
Planting date	Mid-May	Mid-May	Mid-May	Mid-May	Mid-May	Mid-May
Seed rate	90 kg ha^{-1} for wheat	90 kg ha^{-1} for wheat, 1.6 million seeds ha^{-1} for barley hay, and 0.8 million seeds ha^{-1} for pea hay	90 kg ha^{-1} for wheat	90 kg ha^{-1} for wheat, 1.6 million seeds ha^{-1} for barley hay, and 0.8 million seeds ha^{-1} for pea hay	90 kg ha^{-1} for wheat	90 kg ha^{-1} for wheat, 1.6 million seeds ha^{-1} for barley hay, and 0.8 million seeds ha^{-1} for pea hay
Harvest date	September for wheat	August for pea/barley mixture hay and September for wheat	September for wheat	September for wheat.	September for wheat	August for pea/barley mixture hay and September for wheat
Grain and residue removal	Wheat grain and aboveground biomass removed	Wheat grain and aboveground biomass including pea/barley hay removed	Wheat grain removed. Sheep grazed on wheat residue	Wheat grain removed. Sheep grazed on wheat residue and pea/barley hay	Wheat grain and aboveground biomass removed	Wheat grain and aboveground biomass including pea/barley hay removed

Weed management practices are chemical, weed control with herbicide application; grazing, weed control by sheep grazing; and mechanical, weed control by tillage. Cropping sequences are CSW continuous spring wheat and W–P/B–F spring wheat–pea/barley mixture hay–fallow

preparation. The size of the main plot was 91.4 m × 76.0 m and split plot 91.4 m × 15.2 m.

Crop management

Nitrogen fertilizer as urea (45 % N) was broadcast to spring wheat and pea/barley mixture hay before planting in mid-May 2009–2011. While N fertilizer was left at the soil surface in the grazing and chemical treatments, it was incorporated to a depth of 15 cm using tillage in the mechanical treatment. Nitrogen fertilization 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 included both soil and fertilizer N, and fertilizer N rates were calculated by deducting soil NO_3-N content to a depth of 60 cm measured after grain and hay harvest in the autumn of the previous year from desired N rates.

This was done to include soil residual N so that the concentration of N in the fertilization rates does not exceed the desired amount. Because 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, Montana) was planted in CSW and W–P/B–F 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) and Austrian winter pea hay (cultivar Arvika, Circle S Seed, Logan, UT) were planted in W–P/B–F. In August and September, total crop biomass (grains, stems, and leaves in spring wheat and stems and leaves in pea/barley mixture hay) was collected 2 day before grain and hay harvest from two 0.5 m^2 areas per plot. Biomass samples were oven dried at 60 °C for 3 day and weighed for dry matter yield determination. Spring wheat grain yield (oven-dried basis) was determined from an area of 1,389 m^2 using a combine harvester after oven-drying a subsample at 60 °C for 3 day. Spring wheat biomass (stems and leaves) was determined by deducting grain yield from total biomass. Biomass of spring wheat after grain harvest and that of pea/barley were removed from the soil for hay with a self-propelled mower-conditioner and square baler in the chemical and mechanical treatments. In the grazing treatment, sheep were allowed to graze over swathed spring wheat biomass and pea/barley mixture forage.

Soil sampling and analysis

Soil samples were collected at the 0–30 cm depth from five locations in the central rows of each sub plot (or 60 cores per main plot) using a hydraulic probe (4 cm inside diameter) in October (a month after crop harvest) of each year. Soil cores were divided into 0–5, 5–15, 15–30 cm depth intervals. A portion ($\approx$10 g) of the sample was oven-dried soil at 105 °C for 24 h to determine soil water content, from which a conversion factor was determined to calculate the mass of the oven-dried soil core. The bulk density of the soil was calculated as follows:

$$\text{Bulk density} = M/\left(3.14 \times d^2 \times L/4\right),$$

where M is mass of the oven-dried soil, d is the inside diameter of the probe, and L is the length of the soil core.

The remainder of each sample was air-dried and ground to pass a 2-mm sieve. The STN concentration in soil samples was determined by using a high combustion C and N analyzer (LECO Corp., St. Joseph, MI) after grinding the sample to 0.5 mm. For determining PON concentration, 10 g soil was dispersed with 30 mL of 5 g L^{-1} sodium hexametaphosphate for 16 h and the solution was poured through a 0.053 mm sieve (Cambardella and Elliott 1992). The solution that passed through the sieve and contained mineral-associated and water-soluble N was oven dried at 50 °C for 3–4 day and total N concentration was determined by using the analyzer as described above. The PON concentration was determined by the difference between STN in the whole-soil and that in the particles that passed through the sieve after correcting for the sand content.

The PNM in air-dried soils was determined by the method described by Haney et al. (2004). Two 10 g soil samples were moistened with water to 50 % field capacity [0.25 m^3 m^{-3} (Aase and Pikul 2000)] and incubated in a 1 L jar at 21 °C for 10 day. At 10 day, one container was removed and extracted with 50 mL of 2*M* KCl for 1 h. The NH_4-N and NO_3-N concentrations in the extract were determined colorimetrically using the modified Griess-Illosvay method with an autoanalyzer (Lachat Instrument, Loveland, CO) where NH_4-N and NO_3-N were reduced to NO_2-N using the Cd reduction and indophenol blue reaction (Mulvaney 1996). The PNM concentration was determined by the difference between the sum of NH_4-N and NO_3-N concentrations before and after incubation. The other container with moist soil was subsequently used for determining MBN concentration by the modified fumigation-incubation method for air-dried soils (Franzluebbers et al. 1996). This container was incubated twice because MBN determination required moist-soil. The method also required mineralizable C to be flushed out during the first incubation (Franzluebbers et al. 1996). The moist soil was fumigated with ethanol-free chloroform for 24 h and incubated for 10 day at 21 °C, after which NH_4-N and NO_3-N concentrations were determined as above after extracting with KCl. The MBN concentration was calculated by the difference between the sum of NH_4-N and NO_3-N concentrations in the sample before and after fumigation-incubation and using a correction factor of 2.44 (Voroney and Paul 1984).

The contents (Mg N ha^{-1} or kg N ha^{-1}) of STN, PON, PNM, and MBN at individual depth increments were calculated by multiplying their concentrations (g N kg^{-1} or mg N kg^{-1}) by the bulk density and thickness of the soil layer. Because the bulk density at all depths was not significantly influenced by treatments and years, values of 1.20, 1.34, and 1.61 Mg m^{-3} at 0–5, 5–15, and 15–30 cm, respectively, averaged across treatments and years, were used to convert concentrations of N fractions into contents. Total contents at 0–30 cm were determined by summing the contents from individual depths.

Data analysis

Data for soil N fractions were analyzed by using the Analysis of Covariance in the SAS-MIXED model, after considering STN in 2008 as a covariate (Littell et al. 2006). Weed management practice was considered as the main plot treatment and a fixed effect, cropping sequence as the split plot treatment and another fixed effect, year as a repeated measure variable, and replication and replication × weed management practice interaction as random effects. Since W–P/B–F had three cropping phases with each phase of the cropping sequence occurring every year, data for soil N parameters were averaged across phases within the sequence, and the average value was used for the cropping sequence for analysis. Means were separated by using the least square means test when treatments and interactions were significant (Littell et al. 2006). Regression analysis was used to determine the rate of change of soil N fractions in treatments with year when their interactions were significant. The timings of 0.5, 1.5, and 2.5 year used in the regression analysis represent the actual periods of soil sampling in October 2009, 2010, and 2011, respectively, since the project was initiated in April 2009. Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

Results

Particulate organic nitrogen

With the elimination of 2008 STN levels for data analysis, PON varied with years at all depths, with significant interactions for weed management practice × cropping sequence and weed management practice × year at 0–30 cm (Table 2). The 2008 STN as the covariate parameter influenced PON at 0–5, 5–15, 0–15, and 0–30 cm. Averaged across years, PON at 0–30 cm was greater in the mechanical than the grazing treatment with CSW. Averaged across cropping sequences, PON at 0–30 cm was greater in the chemical and mechanical than the grazing treatment in 2009 and greater in the mechanical than the chemical and grazing treatments in 2011 (Fig. 1). Based on the linear regression PON with year (Fig. 1), PON at 0–30 cm declined from 0.39 Mg N ha^{-1} $year^{-1}$ in the grazing treatment to 0.58 Mg N ha^{-1} $year^{-1}$ in the chemical treatment from 2009 to 2011 (Table 3). Averaged across treatments, PON at all depths declined from 2009 to 2011 (Table 2).

The proportion of STN in PON, i.e. the PON/STN ratio varied with cropping sequences at 5–15 and 0–15 cm and with years at all depths (Table 2). Significant interactions occurred for weed management practice × cropping sequence at 0–5, 15–30, and 0–30 cm and weed management practice × year at 0–15 cm. The 2008 STN as the covariate parameter influenced the PON/STN ratio at 0–15 and 0–30 cm.

Averaged across years, the PON/STN ratio at 0–5 cm was greater in the mechanical treatment with CSW than the chemical and mechanical treatments with W–P/B–F and the grazing treatment with CSW (Table 2). At 15–30 cm, the PON/STN ratio was greater in the grazing treatment with W–P/B–F or the mechanical treatment with CSW than the grazing treatment with CSW. At 0–30 cm, the PON/STN ratio was greater in the mechanical and chemical treatments with CSW and the grazing treatment with W–P/B–F than the grazing treatment with CSW. Averaged across cropping sequences, the PON/STN ratio at 0–15 cm was greater in the mechanical than the chemical treatment in 2009, but the trend reversed in 2010 (Fig. 1). Using linear regression of PON/STN ratio with year (Fig. 1) from 2009 to 2011, the PON/STN ratio at 0–15 cm declined from 0.04 Mg Mg^{-1} $year^{-1}$ in the chemical treatment to 0.05 Mg Mg^{-1} $year^{-1}$ in the grazing and mechanical treatments (Table 3). Averaged across weed management practices and years, the PON/STN ratio at 5–15 and 0–15 cm was greater with CSW than W–P/B–F (Table 2). Averaged across treatments, the PON/STN ratio at all depths declined from 2009 to 2011.

Table 2 Effects of weed management practice and cropping sequence on soil PON content and the PON/STN ratio at the 0–30 cm depth averaged across years

Years	Weed management[a]	Cropping sequence[b]	PON content at soil depth (Mg N ha^{-1})					PON/STN ratio at soil depth (Mg Mg^{-1})				
			0–5 cm	5–15 cm	15–30 cm	0–15 cm	0–30 cm	0–5 cm	5–15 cm	15–30 cm	0–15 cm	0–30 cm
	Chemical	CSW	0.39	0.63	0.45	0.99	1.43	0.24	0.19	0.11	0.20	0.16
		W–P/B–F	0.33	0.46	0.54	0.80	1.31	0.20	0.14	0.12	0.16	0.15
	Grazing	CSW	0.34	0.41	0.25	0.84	0.91	0.20	0.15	0.08	0.18	0.12
		W–P/B–F	0.35	0.58	0.53	0.90	1.48	0.22	0.17	0.14	0.18	0.17
	Mechanical	CSW	0.40	0.60	0.55	0.90	1.53	0.25	0.19	0.14	0.21	0.18
		W–P/B–F	0.33	0.50	0.46	0.99	1.35	0.20	0.15	0.12	0.17	0.15
	LSD (0.05)		NS	NS	NS	NS	0.62	0.05	NS	0.06	NS	0.04
	Mean	CSW	0.37a[c]	0.58a	0.41a	0.95a	1.36a	0.23a	0.18a	0.11a	0.20a	0.16a
		W–P/B–F	0.34a	0.51a	0.51a	0.85a	1.36a	0.21a	0.15b	0.13a	0.17b	0.15a
2009			0.41a	0.74a	0.69a	1.16a	1.83a	0.25a	0.22a	0.16a	0.23a	0.20a
2010			0.39a	0.49b	0.39b	0.90b	1.26b	0.24a	0.16b	0.11b	0.19b	0.15b
2011			0.27b	0.35b	0.31b	0.63c	0.92c	0.17b	0.12c	0.09b	0.14c	0.12c
	Significance											
	Weed management (W)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Cropping sequence (S)		NS	NS	NS	NS	NS	NS	*	NS	*	NS
	W × S		NS	NS	NS	NS	*	*	NS	*	NS	*
	Year (Y)		***	***	***	***	***	***	***	**	***	***
	W × Y		NS	NS	NS	NS	*	NS	NS	NS	*	NS
	S × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	W × S × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	STN08[d]		**	*	NS	***	***	NS	NS	NS	*	**

NS not significant

* Significant at $P \leq 0.05$; ** Significant at $P \leq 0.01$; *** Significant at $P \leq 0.001$

[a] Weed management practices are chemical, weed control with herbicide application; grazing, weed control by sheep grazing; and mechanical, weed control by tillage

[b] Cropping sequences are *CSW* continuous spring wheat, *W–P/B–F* spring wheat–pea/barley mixture hay–fallow

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

[d] STN levels in 2008 used as covariate for data analysis

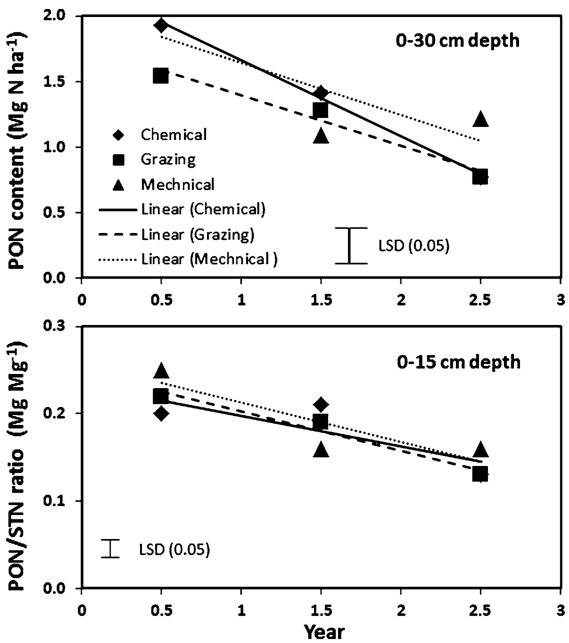

Fig. 1 Relationship between soil PON content at the 0–30 cm depth and PON/STN ratio at the 0–15 cm depth with year as influenced by weed management practices. Weed management practices are chemical, weed control with herbicide application; grazing, weed control by sheep grazing; and mechanical, weed control by tillage. Regression coefficients are shown in Table 3. Years of 0.5, 1.5, and 2.5 represent timing of soil sampling in October 2009, 2010, and 2011, respectively, since the experiment started in April 2009

Microbial biomass nitrogen

Eliminating the effect of STN in 2008, MBN at all depths varied among years, with significant weed management practice × cropping sequence interaction at 5–15, 0–15, and 0–30 cm (Table 4). The 2008 STN as the covariate parameter influenced MBN at all depths. Averaged across years, MBN at 5–15 cm was greater in the chemical treatment with CSW than the chemical treatment with W–P/B–F, the grazing treatment with CSW, or the mechanical treatment with W–P/B–F. The MBN was lower in W–P/B–F than CSW in the chemical treatment, but the trend reversed in the grazing treatment. With CSW, MBN was also lower in the grazing than the chemical treatment. At 0–15 cm, MBN was greater in the mechanical than the grazing treatment with CSW. At 0–30 cm, MBN was lower in the grazing treatment with CSW than the other treatments, except the chemical treatment with W–P/B–F. Averaged across treatments, MBN declined from 2009 to 2011 at all depths, except at 15–30 cm.

The proportion of STN in MBN, i.e. the MBN/STN ratio also varied with years at all depths, with significant weed management practice × cropping sequence interaction at 5–15, 0–15, and 0–30 cm, similar to MBN (Table 4). The MBN/STN ratio at 5–15 cm was greater in the chemical or mechanical than the grazing treatment with CSW. At 0–15 cm, the MBN/STN ratio was greater in the mechanical treatment with CSW than the grazing treatment with CSW and the mechanical treatment with W–P/B–F. At 0–30 cm, the MBN/STN ratio was greater in the mechanical and chemical treatments with CSW than the chemical treatment with W–P/B–F or the grazing treatment with CSW. Averaged across treatments, the MBN/STN ratio also declined from 2009 to 2011 at all depths, except at 15–30 and 0–30 cm.

Potential nitrogen mineralization

As with MBN, eliminating the effect of 2008 STN levels, PNM varied with weed management practices at 15–30 cm and years at all depths (Table 5). Significant interactions occurred for weed management practice × year at 15–30 cm and cropping sequence × year at 5–15 cm. The 2008 STN as the covariate parameter influenced PNM at all depths, except at 5–15 cm.

Averaged across cropping sequences, PNM at 15–30 cm was greater in the chemical than the grazing and mechanical treatments in 2009, but was greater with the mechanical than the chemical and grazing treatments in 2011 (Fig. 2). Averaged across weed management practices, PNM at 5–15 cm was greater with W–P/B–F than CSW in 2010 (Fig. 3). Based on the linear regression of PNM with year (Fig. 2) from 2009 to 2011, PNM at 15–30 cm declined from 2.25 kg N ha^{-1} year^{-1} in the grazing treatment to 5.80 kg N ha^{-1} year^{-1} in the chemical treatment, but increased at 1.60 kg N ha^{-1} year^{-1} in the mechanical treatment (Table 3). Similarly, using linear regression (Fig. 3), PNM at 5–15 cm declined from 1.80 kg N ha^{-1} year^{-1} in CSW to 5.05 kg N ha^{-1} year^{-1} in W–P/B–F. Averaged across cropping sequences and years, PNM at 15–30 cm was greater in the chemical and mechanical than the grazing treatment (Table 5). Averaged across treatments,

Table 3 Regression coefficients for the linear relationship between soil PON content, PON/STN ratio, PNM content, and PNM/STN ratio with year for Figs. 1, 2, and 3

Parameter	Soil depth	Treatment	Regression coefficient		
			a	b	R^2
PON (Mg N ha^{-1})	0–30 cm	Chemical[a]	2.24	−0.58	0.99
		Grazing[a]	1.77	−0.39	0.97
		Mechanical[a]	2.04	−0.40	0.63
PON/STN ratio (Mg Mg^{-1})	0–15 cm	Chemical	0.23	−0.04	0.64
		Grazing	0.25	−0.05	0.96
		Mechanical	0.26	−0.05	0.75
PNM (kg N ha^{-1})	15–30 cm	Chemical	21.6	−5.80	0.56
		Grazing	10.7	−2.25	0.97
		Mechanical	11.4	1.60	0.16
PNM (kg N ha^{-1})	5–15 m	CSW[b]	14.6	−1.80	0.19
		W–P/B–F[b]	20.7	−5.05	0.94
PNM/STN ratio (kg Mg^{-1})	15–30 cm	Chemical	4.50	−0.86	0.41
		Grazing	2.66	−0.33	0.69
		Mechanical	2.68	0.68	0.36
PNM/STN ratio (kg Mg^{-1})	5–15 cm	CSW	4.32	−0.37	0.09
		W–P/B–F	5.83	−1.20	0.79

[a] Weed management practices are chemical, weed control with herbicide application; grazing, weed control by sheep grazing; and mechanical, weed control by tillage

[b] Cropping sequences are CSW, continuous spring wheat; W–P/B–F, spring wheat–pea/barley mixture hay–fallow

PNM declined from 2009 to 2011 at all depths, except at 15–30 and 0–30 cm.

The proportion of STN in PNM, i.e. the PNM/STN ratio also varied with years at all depths, with significant interactions for weed management practice × year at 15–30 cm and cropping sequence × year at 5–15 cm (Table 5). The 2008 STN as the covariate parameter influenced the PNM/STN ratio at 0–5 cm. Averaged across cropping sequences, the PNM/STN ratio at 15–30 cm was greater in the chemical than the grazing and mechanical treatments in 2009, but was greater in the mechanical than the chemical and grazing treatments in 2011 (Fig. 2). Averaged across weed management practices, the PNM/STN ratio at 5–15 cm was greater with W–P/B–F than CSW in 2010, but the trend reversed in 2011 (Fig. 3). Using linear regression (Fig. 2), the PNM/STN ratio at 15–30 cm decreased from 0.33 kg Mg^{-1} $year^{-1}$ in the grazing treatment to 0.86 kg Mg^{-1} $year^{-1}$ in the chemical treatment, but increased at 0.68 kg Mg^{-1} $year^{-1}$ in the mechanical treatment from 2009 to 2011 (Table 3). Similarly, from linear regression (Fig. 3), the PNM/STN ratio at 5–15 cm decreased from 0.37 kg Mg^{-1} $year^{-1}$ in CSW to 1.20 kg Mg^{-1} $year^{-1}$ in W–P/B–F. Averaged across treatments, the PNM/STN ratio declined from 2009 to 2011 at all depths, except at 15–30 and 0–30 cm, a case similar to that observed for PNM (Table 5).

Discussion

Higher crop biomass N, followed by incorporation of residue to a greater depth due to tillage probably increased PON at 0–30 cm in the mechanical treatment with CSW (Table 2). Although spring wheat biomass N was greater with W–P/B–F, annualized biomass N was higher with CSW due to continuous cropping than W–P/B–F where absence of crops during fallow reduced biomass N (Barsotti et al. 2013). Because C/N ratio of spring wheat (41) was greater than pea/barley mixture (29) (Barsotti et al. 2013), it could be possible that the incorporation of greater amount of crop residue with higher C/N ratio into the soil increased PON due to slower decomposition of the residue. Residues with higher C/N ratio decompose more slowly than residues with lower C/N ratio (Kuo et al. 1997). Increased amount of crop residue N returned to the soil increased PON in eastern Montana (Sainju et al. 2009), but no-till increased PON compared to conventional till in Texas (Franzluebbers et al. 1995). Probably differences in soil and climatic conditions between locations influenced decomposition of crop residue N and therefore PON.

Lower PON in the grazing treatment with CSW was probably due to lower proportion of labile than nonlabile fractions of organic matter through feces and urine to the soil, thereby reducing PON relative to STN. It could be possible that sheep consumed most of the labile portion of crop residue, thereby returning greater proportion of nonlabile organic matter through feces and urine to the soil that are largely linked with clay fractions and protected from mineralization by soil microorganisms. Sheep were grazed day and night for a shorter duration with CSW than W–P/B–F where additional grazing during the summer fallow may have returned more N through feces and urine to the soil, thereby increasing PON in the grazing treatment with W–P/B–F. Cattle (*Bos taurus* L.) grazing reduced particular organic matter content compared to no grazing on annual summer cover crop residue (Franzluebbers and Stuedemann 2008), but grazing on perennial bermudagrass (*Cynodon doctylon* [L.] Pers.) increased the content compared to non-grazed and hayed residue (Franzluebbers and Stuedemann 2003). It could be possible that sheep grazing in annual cropping systems may have removed both above- and part of the belowground (root) residue that may have been killed after grain harvest, thereby reducing N input. In perennial cropping systems, root biomass can be higher and roots grow to a greater depth than annual cropping systems (Ma et al. 2000). As a result, perennial roots may not be easily removed by animal during grazing, rather grazing may have stimulated root growth and therefore increased particulate organic matter in perennial compared to annual cropping systems (Franzluebbers and Stuedemann 2003, 2008). Sheep grazing, however, reduced the rate of PON loss from 2009 to 2011 compared to the chemical treatment (Fig. 1; Table 3) where removal of aboveground biomass for hay increased the loss. This suggests that it may take long time to enrich PON in the grazing treatment through increased addition of N from feces and urine to the soil. Reducing the intensity of grazing by lowering the stocking rate of sheep in the plot, however, may reduce the rate of PON loss and enhance its level. Although aboveground biomass was also removed for hay in the mechanical treatment, incorporation of left-over stubble residue into the soil due to tillage appeared to reduce PON loss in this treatment compared to the chemical treatment. Reduction of PON from 2009 to 2011, regardless of treatments, was probably a result of crop residue removal. Crop residue removal can reduce soil N storage compared to non-removal (Sainju et al. 2012; Barsotti et al. 2013).

As with PON, the greater PON/STN ratio at 0–30 cm in the mechanical treatment with CSW than the other treatments (Table 2) indicates that slower decomposition of spring wheat residue due to higher C/N ratio probably increased PON relative to STN. The trend in reduction in the PON/STN ratio among treatments from 2009 to 2011 was similar to reduction in PON. Although the 2008 STN level at 0–120 cm was higher in sheep grazing with CSW (Sainju et al. 2010), Barsotti et al. (2013) from the same experiment found that average STN at 5–15 cm from 2009 to 2011 was lower in the grazing treatment with CSW than the other treatments. This suggests that both PON and STN declined in the grazing treatment with CSW, but PON may have been reduced more than STN due to lower amount of labile organic matter returned to the soil through feces during sheep grazing. Reduced rate of decline of the PON/STN ratio compared to PON (Table 3) suggests that STN changes more slowly than PON. The proportion of STN in PON observed in this experiment was within or slightly lower than the reported values of 18–24 % in the northern Great Plains, USA (Sainju et al. 2009).

Increased crop biomass N, followed by relatively undisturbed soil condition due to no-tillage may have increased MBN at 5–15 and 0–30 cm in the chemical treatment with CSW (Table 4). Several researchers (Franzluebbers et al. 1995; Sainju et al. 2012) have also observed greater MBN in no-till than conventional till or in no-till continuous cropping than conventional till crop-fallow systems. In contrast, incorporation of residue with higher C/N ratio into the soil may have increased MBN at 0–15 cm in the mechanical treatment with CSW. Since addition of crop residue with higher C/N ratio can immobilize N (Kuo et al. 1997), it could be possible that incorporation of spring wheat residue increased MBN in the mechanical treatment with CSW. Sainju et al. (2009)

Table 4 Effects of weed management practice and cropping sequence on soil MBN content and the MBN/STN ratio at the 0–30 cm depth from 2009 to 2011

Years	Weed management[a]	Cropping sequence[b]	MBN content at soil depth (kg N ha^{-1})					MBN/STN ratio at soil depth (kg Mg^{-1})				
			0–5 cm	5–15 cm	15–30 cm	0–15 cm	0–30 cm	0–5 cm	5–15 cm	15–30 cm	0–15 cm	0–30 cm
	Chemical	CSW	76	162	133	233	366	45.9	48.5	35.1	47.1	42.2
		W–P/B–F	81	132	112	211	320	48.4	41.7	27.7	43.2	36.1
	Grazing	CSW	82	87	82	185	240	49.9	31.8	26.8	39.0	33.0
		W–P/B–F	81	142	110	216	332	52.4	43.5	29.0	46.2	38.9
	Mechanical	CSW	93	149	124	243	365	57.7	46.5	33.0	50.5	43.2
		W–P/B–F	77	130	122	209	336	48.0	39.6	32.3	42.7	38.3
	LSD (0.05)		NS	30	NS	58	86	NS	11.8	NS	7.8	6.1
2009			98a[c]	162a	147a	261a	403a	59.1a	47.6a	34.3a	51.3a	43.3a
2010			76b	124b	94b	201b	293b	47.2b	39.6b	27.3b	42.3b	36.2b
2011			71b	114b	101b	187b	284b	44.8b	38.6b	30.4ab	40.7b	36.3a
	Significance											
	Weed management (W)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Cropping sequence (S)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	W × S		NS	***	NS	*	**	NS	**	NS	*	*
	Year (Y)		***	***	***	***	***	***	**	*	***	**
	W × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	S × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	W × S × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	STN08[d]		*	**	*	***	***	NS	NS	NS	NS	NS

NS not significant

* Significant at $P \leq 0.05$; ** Significant at $P \leq 0.01$; *** Significant at $P \leq 0.001$

[a] Weed management practices are chemical, weed control with herbicide application; grazing, weed control by sheep grazing; and mechanical, weed control by tillage

[b] Cropping sequences are CSW, continuous spring wheat; W–P/B–F, spring wheat–pea/barley mixture hay–fallow

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

[d] STN levels in 2008 used as covariate for data analysis

Table 5 Effects of weed management practice and cropping sequence on soil PNM content and the PNM/STN ratio at the 0–30 cm depth from 2009 to 2011

Weed management[a]	Years	PNM content at soil depth (kg N ha^{-1})					PNM/STN ratio at soil depth (kg Mg^{-1})				
		0–5 cm	5–15 cm	15–30 cm	0–15 cm	0–30 cm	0–5 cm	5–15 cm	15–30 cm	0–15 cm	0–30 cm
	2009	10.3a[b]	16.6a	15.1a	27.0a	41.5a	6.21a	4.84a	3.46a	5.27a	4.44a
	2010	6.9b	11.1b	8.1b	17.9ab	25.8b	4.24b	3.59b	2.37b	3.82b	3.19b
	2011	5.4b	9.8b	10.8b	15.4b	26.2b	3.37b	3.27b	3.19ab	3.37b	3.28b
Chemical		7.1a	13.4a	12.9a	20.4a	33.4a	4.20a	4.07a	3.21a	4.11a	3.72a
Grazing		7.5a	10.1a	7.4b	17.7a	24.3a	4.55a	3.25a	2.37a	3.67a	2.98a
Mechanical		8.0a	14.0a	13.8a	22.8a	35.9a	5.08a	4.38a	3.19a	4.69a	4.21a
Significance											
Weed management (W)		NS	NS	*	NS	NS	NS	NS	NS	NS	NS
Cropping sequence (S)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W × S		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year (Y)		**	**	***	***	***	**	*	*	**	**
W × Y		NS	NS	**	NS	NS	NS	NS	**	NS	NS
S × Y		NS	*	NS	NS	NS	NS	**	NS	NS	NS
W × S × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
STN08[c]		**	NS	*	**	*	*	NS	NS	NS	NS

NS not significant

* Significant at $P \leq 0.05$; ** Significant at $P \leq 0.01$; *** Significant at $P \leq 0.001$

[a] Weed management practices are chemical, weed control with herbicide application; grazing, weed control by sheep grazing; and mechanical, weed control by tillage

[b] Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test

[c] STN levels in 2008 used as covariate for data analysis

also reported greater MBN in the subsurface soil under the conventional till than the no-till system due to residue incorporation to a greater depth. Consumption of most of the labile portion of crop residue by sheep and return of higher proportion of nonlabile organic matter in the digested material through feces and urine may have reduced MBN in the grazing treatment with CSW, a case similar to that observed for PON. Although moderate cattle grazing in perennial cropping systems can increase soil microbial biomass compared to non-grazing or hayed system (Franzluebbers and Stuedemann 2003), our results showed the reverse trend of grazing on MBN in annual cropping systems, a case similar to that obtained for lower microbial biomass due to cattle grazing than no grazing in annual cropping systems (Franzluebbers and Stuedemann 2008). It was not known if sheep grazed heavily in our experiment. Heavy grazing, however, can reduce soil microbial biomass (Holt 1997). Reduction in N substrate availability as a result of crop residue removal probably reduced MBN from 2009 to 2011.

Sheep grazing similarly reduced the proportion of STN in MBN in the grazing treatment while increasing in the chemical or mechanical treatment with CSW (Table 4), indicating MBN as an active N fraction for rapid changes due to management practices compared to STN. The fact that sheep grazing impacted little in MBN or the MBN/STN ratio with W–P/B–F compared to CSW was probably related to longer duration of grazing, a case similar to that observed for PON. Barsotti et al. (2013) also found greater STN with sheep grazing with W–P/B–F than CSW due to longer period of grazing. The proportion of STN in MBN obtained in this experiment was within or slightly greater than the reported values of 1.7–4.3 % in the northern Great Plains (Sainju et al. 2009, 2012).

The lower PNM at 15–30 cm in the grazing than the chemical and mechanical treatments in 2009 and 2011 (Fig. 2) was probably resulted from the reduced proportion of labile compared to nonlabile organic matter returned to the soil through feces and urine, a case similar to those observed for PON and MBN. Large variations in PNM from 2009 to 2011 in the chemical and mechanical treatments were probably related to crop biomass production due to changes in precipitation from year to year, but consumption of most of the residue by sheep during grazing probably reduced the variability in PNM in the grazing treatment. Our results were similar to those observed for reduced N mineralization by cattle grazing compared to no grazing in annual cropping systems (Franzluebbers and Stuedemann 2008), but increased N mineralization with grazing in perennial cropping systems (Frank and Groffman 1998). The type of the animal (e.g. cattle vs. sheep) grazed, reflecting the amount of N inputs in feces and urine, their distribution in the soil, and cropping system (perennial vs. annual cropping system) probably influenced N mineralization. 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 grazing (Abaye et al. 1997). In contrast, increased N input from feces and urines due to longer duration of grazing may have increased PNM at 5–15 cm with W–P/B–F than CSW in 2010 (Fig. 3). As with PON, sheep grazing and residue incorporation into the soil probably reduced the rate of PNM loss in the grazing and mechanical

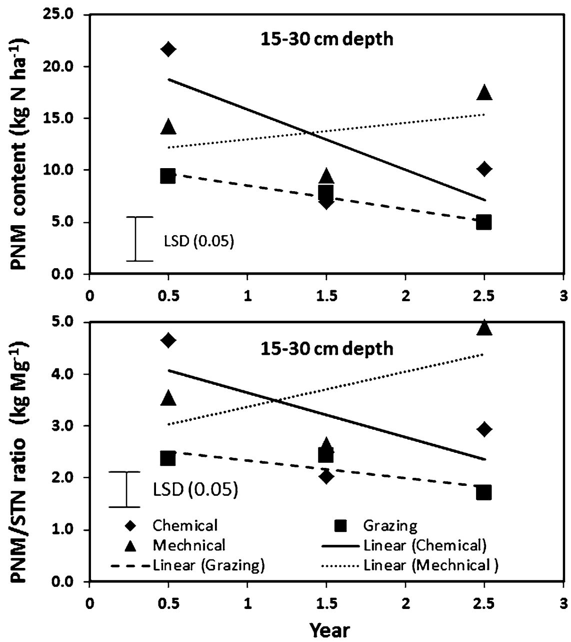

Fig. 2 Relationship between soil PNM content and the PNM/STN ratio at the 15–30 cm depth with year as influenced by weed management practices. Weed management practices are chemical, weed control with herbicide application; grazing, weed control by sheep grazing; and mechanical, weed control by tillage. Regression coefficients are shown in Table 3. Years of 0.5, 1.5, and 2.5 represent timing of soil sampling in October 2009, 2010, and 2011, respectively, since the experiment started in April 2009

treatments compared to the chemical treatment from 2009 to 2011 (Table 3). Higher rate of PNM loss with W–P/B–F than CSW, however, was probably a result of reduced amount of residue returned to the soil due to absence of crops during fallow. As with PON and MBN, removal of crop residue probably reduced PNM from 2009 to 2011.

Changes in the PNM/STN ratio due to weed management practices and cropping sequences from 2009 to 2011 (Figs. 2, 3) were similar to those for PNM, suggesting that PNM may be another sensitive indicator to changes in soil N levels compared to STN. Increased proportion of labile relative to nonlabile organic matter through feces and urine returned to the soil may have reduced the PNM/STN ratio at 15–30 cm with sheep grazing compared to the chemical and mechanical treatments in 2009 and 2011, but longer duration of grazing increased the ratio at 5–15 cm with W–P/B–F compared to CSW in 2010. Our proportions of STN in PNM of 0.17–0.68 % were within the ranges of 0.07–1.50 % reported by several researchers (Sainju et al. 2009, 2012).

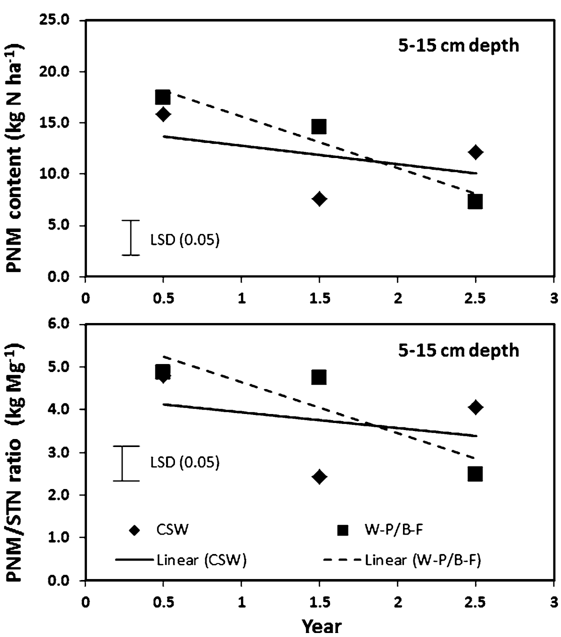

Fig. 3 Relationship between soil PNM content at the 0–15 cm depth and the PON/STN ratio at the 5–15 cm depth with year as influenced by cropping sequence. Cropping sequences are CSW, continuous spring wheat; W–P/B–F, spring wheat–pea/barley mixture hay–fallow. Regression coefficients are shown in Table 3. Years of 0.5, 1.5, and 2.5 represent timing of soil sampling in October 2009, 2010, and 2011, respectively, since the experiment started in April 2009

Results from this study were contrary to our hypotheses that sheep grazing would increase PON, MBN, and PNM under CSW compared to tillage and herbicide application for weed control under W–P/B–F. Based on these results, sheep grazing may be a viable option to increase soil N fractions and N cycling compared to tillage and herbicide application for weed control only in the long-run in dryland annual continuous cropping systems. This is because grazing increased nonlabile relative to labile soil N fraction, resulting in increased N conservation and longer time requirement for N mineralization. Reducing grazing intensity, either by lowering the number of sheep per plot, duration of grazing, or both, thereby increasing the amount of crop residue N returned to the soil may enhance soil microbial activity and N mineralization.

Conclusions

Removal of crop residue either due to haying or to sheep grazing reduced PON, MBN, and PNM in all treatments. Sheep grazing reduced PON, MBN, and PNM compared to herbicide application in the chemical treatment and tillage in the mechanical treatment for weed control in contrast to our hypothesis. The effect was more pronounced with CSW than W–P/B–F where duration of sheep grazing was longer. Rates of decline of PON and PNM from 2009 to 2011 were greater in the chemical than the grazing and mechanical treatments and greater with W–P/B–F than CSW. Although sheep grazing reduced soil N fractions, slower rate of decline in these fractions from 2009 to 2011 suggests that it may take more than 3 years to enhance soil microbial activity and N mineralization and therefore soil productivity with grazing compared to herbicide application and tillage for weed control under dryland continuous cropping systems in the northern Great Plains, USA. Reducing grazing intensity can enhance microbial activity and N mineralization due to increased amount of crop residue returned to the soil.

Acknowledgments We appreciate the excellent technical supports provided by Ashlee Johnson for soil and plant sample collections in the field and Jana Seright and Rene' France for analysis in the laboratory. We also thank Drs. Hayes

Goosey and Zachary Miller for farm management and research coordination. We acknowledge the funding for this project from USDA-CSREES-ICGP-0002154.

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