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ORIGINAL ARTICLE

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Abstract Management practices may influence dryland soil N cycling. We evaluated the effects of tillage, crop rotation, and cultural practice on dryland crop biomass (stems and leaves) N, surface residue N, and soil N fractions at the 0–20 cm depth in a Williams loam from 2004 to 2008 in eastern Montana, USA. Treatments were two tillage practices (no-tillage [NT] and conventional tillage [CT]), two crop rotations (continuous spring wheat [*Triticum aestivum* L.] [CW] and spring wheat-barley [*Hordeum vulgaris* L.] hay-corn [*Zea mays* L.]-pea [*Pisum sativum* L.] [W-B-C-P]), and two cultural practices (regular [conventional seed rates and plant spacing, conventional planting date, broadcast N fertilization, and reduced stubble height] and ecological [variable seed rates and plant spacing, delayed planting, banded N fertilization, and increased stubble height]). Nitrogen fractions were soil total N (STN), particulate organic N (PON), microbial biomass N (MBN), potential N mineralization (PNM), NH_4–N, and NO_3–N. Crop biomass N was 30 % greater in W-B-C-P than in CW in 2005. Surface residue N was 30–34 % greater in NT with the regular and ecological practices than in CT with the regular practice. The STN, PON, and MBN at 10–20 and 0–20 cm were 5–41 % greater in NT or CW with the regular practice than in CT or CW with the ecological practice. The PNM at 5–10 cm was 22 % greater in the regular than in the ecological practice. The NH_4–N and NO_3–N contents at 10–20 and 0–20 cm were greater in CT with W-B-C-P and the regular practice than with most other treatments in 2007. Surface residue and soil N fractions, except PNM and NO_3–N, declined from autumn 2007 to spring 2008. In 2008, NT with W-B-C-P and the regular practice gained 400 kg N ha^{-1} compared with a loss of 221 kg N ha^{-1} to a gain of 219 kg N ha^{-1} in other treatments. No-tillage with the regular cultural practice increased surface residue and soil N storage but conventional tillage with diversified crop rotation and the regular practice increased soil N availability. Because of continuous N mineralization, surface residue and soil N storage decreased without influencing N availability from autumn to the following spring.

Keywords Crop residue nitrogen · Labile nitrogen fractions · Management practices · Nitrogen cycling, Nitrogen storage

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Introduction

In the northern Great Plains, USA, N storage in soil and crop residue under dryland cropping systems remains a challenge because of lower crop residue N returned to the soil due to limited precipitation and shorter growing season than in humid regions (Campbell et al. 1989; Sainju et al. 2009a). The conventional farming system (CT with crop-fallow) further reduces soil N storage because of increased erosion and mineralization of organic N and reduction in plant residue N returned to the soil due to absence of crops during fallow (Bowman et al. 1999; Campbell et al. 2000). Studies have shown that long-term tillage with crop-fallow has reduced soil N storage by 30–50 % in the last 50–100 years (Haas et al. 1974; Peterson et al. 1998). Use of improved soil and crop management practices, such as NT with increased cropping intensity, however, can increase dryland STN and N fractions to a depth of 20 cm compared to CT with crop-fallow (Sherrod et al. 2003; Sainju et al. 2009a). The NT system can also conserve soil water more than CT, which can increase cropping intensity due to efficient water use by crops (Farhani et al. 1998; Peterson et al. 2001).

Diversified crop rotation is an enhanced approach to reduce the risk of crop failure and improve water-use and nutrient efficiency as opposed to monocropping in water-limited dryland farming systems (Vigil et al. 1997; Miller et al. 2002). Including pea in rotation with spring wheat and barley not only sustains their yields by efficiently utilizing soil water but also reduces N fertilization rates by supplying N from pea residue due to its higher N concentration (Miller et al. 2002; Sainju et al. 2009b; Sainju and Lenssen 2011). This is because pea uses less soil water than spring wheat and barley, thereby leaving more water available for succeeding crops and influencing their yields (Miller et al. 2002; Lenssen et al. 2007). Similarly, forages in rotation with cereals maintain both cereal and forage yields by efficiently utilizing soil water, because forages are harvested earlier for hay than cereals, thereby leaving more water available for succeeding crops (Entz et al. 2002; Lenssen et al. 2010). Other benefits of crop rotation include control of weeds, diseases, and pests (Vigil et al. 1997; Miller et al. 2002), reduction in farm inputs, and improvement in economic and environmental sustainability (Gregory et al. 2002).

One of the major problems in dryland farming systems is weed control, especially in NT cropping systems. Several cultural practices that include high seeding rate of crops, banded fertilization, delayed planting, and increased retention of crop residue, have been effective in controlling weeds (Entz et al. 2002; Strydhorst et al. 2008). The effect of such practices on soil N storage and mineralization in dryland cropping systems is not known.

For managing N availability to crops, a better understanding of soil N cycling is needed. Some of the important parameters of soil N cycling are STN, PON, MBN, PNM, NH_4–N, and NO_3–N. Changes in STN due to management practices usually occur slowly because of a large pool size and inherent spatial variability (Franzluebbers et al. 1995). Therefore, N parameters other than STN need to be considered to reflect changes in soil productivity and nutrient status (Franzluebbers et al. 1995; Bezdicek et al. 1996). Biologically active fractions of STN, such as MBN (N stored in the body of microorganisms) and PNM (N mineralization), that change rapidly with time (e.g. within a growing season) due to management practices, could 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). The PON is an intermediate N fraction between active and slow fractions that also changes rapidly due to changes in management practices (Cambardella and Elliott 1992). Available fractions of N for crop uptake or soil residual N after crop harvest are NH_4–N and NO_3–N that can be lost due to leaching, volatilization, denitrification, or surface runoff (Wood et al. 1990; Sainju et al. 2009a).

Because of the short growing season due to cold weather and lack of enough time for sampling before crop planting in the spring, soil samples are normally taken after harvest in the autumn for testing N levels and recommending N fertilizer rates for succeeding crops in the next year in the northern Great Plains (Eastern Agricultural Research Center 1997). As a result, N fertilizers are applied in the autumn instead of spring in the succeeding year. This results in substantial loss of N due to leaching, surface runoff, volatilization, and denitrification. To reduce this loss, it is recommended that soil tests be done and N fertilizers applied before planting in the spring (Eastern Agricultural Research Center 1997). Since N mineralization can continue during the winter, it could be possible that N levels vary in surface residue and soil samples collected in the autumn and spring. We hypothesized that NT with diversified crop rotation and the ecological cultural practice to spring wheat in the rotation (variable seed rates and plant spacing, delayed planting, banded fertilization, and increased

Table 1 Monthly, annual (January–December), and crop growing season (April–October) total precipitation at the study site

Month	Total precipitation (mm)				
	2004	2005	2006	2007	68-year average
April	7	2	80	21	29
May	53	83	44	128	50
June	45	115	55	49	72
July	31	36	30	21	54
August	15	19	36	8	37
September	36	2	67	19	34
October	27	26	10	9	25
November	3	18	1	0	12
April–October	217	301	322	253	311
January–December	284	324	339	280	357

stubble height) would increase surface residue and soil N levels and N balance compared to CT with monocropping and the regular cultural practice, regardless of sampling time, and that surface residue and soil N levels would decline from the autumn to the following spring. Our objectives were to: (1) examine the amount of dryland crop biomass (stems and leaves) N returned to the soil as influenced by tillage, crop rotation, and cultural practice from 2004 to 2007 in eastern Montana, USA, (2) quantify their effects on soil surface residue N, STN, PON, MBN, PNM, NH_4–N, and NO_3–N contents and estimated N balance at the 0–20 cm depth, and (3) measure changes in surface residue and soil N fractions from autumn 2007 to spring 2008.

Materials and methods

Experimental site and treatments

From 2004 to 2008, the experiment was carried out on a dryland farm site, 8 km northwest of Sidney (47°46′N, 104°16′W; elevation 690 m), Montana. The climate is semiarid, with mean monthly air temperature ranging from −8 °C in January to 23 °C in July and August, and mean annual precipitation (68-year average) of 340 mm, 80 % of which occurs during the crop growing season (April–October) (Table 1). The soil is a Williams loam (fine-loamy, mixed, superactive, frigid, Typic Argiustolls) with 350 g kg^{-1} sand, 325 g kg^{-1} silt, 325 g kg^{-1} clay, and 6.1 pH at the 0–20 cm depth. The STN concentration and bulk density at 0–5 cm prior to the initiation of the experiment in April 2004 were 1.15 g N kg^{-1} and 1.35 Mg m^{-3} and at 5–20 cm were 1.07 g N kg^{-1} and 1.44 Mg m^{-3}, respectively. Previous cropping system for the last 10 yr was CT with spring wheat-fallow.

Treatments included two tillage practices (NT and CT), two crop rotations (CW and W-B-C-P), and two cultural practices (regular and ecological). The cultural practices used for crops in the rotation are described in Table 2. Because spring wheat is the major crop in the area, early and late planting dates and

Table 2 Description of cultural practices (regular and ecological) used for crops in the rotation

Crop	Cultural practice	Seeding rate (million seeds ha^{-1})	N fertilization at planting	Planting date	Stubble height (cm)
Spring wheat	Regular	2.23	Broadcast	Early to mid April	20
	Ecological	2.98	Banded	Early to mid May	30
Pea	Regular	0.60	Broadcast	Early to mid April	5
	Ecological	0.92	Banded	Early to mid April	5
Barley hay	Regular	2.23	Broadcast	Early to mid April	5
	Ecological	2.98	Banded	Early to mid April	5
Corn	Regular	0.04	Broadcast	Early May	5
	Ecological	0.05	Banded	Early May	5

changes in stubble heights were occurred only in this crop. The NT plots were left undisturbed, except for applying fertilizer and planting crops in rows. The CT plots were tilled one to two times a year with a field cultivator to a depth of 7–8 cm for seedbed preparation and weed control. Each phase of the crop rotation was present in every year. Treatments were arranged in a split-plot design in randomized complete block with three replications. Tillage was considered as the main-plot and the factorial combination of crop rotation and cultural practice as the split-plot treatment. The split plot size was 12.2 m × 12.2 m.

Crop management

At planting in April, 2004 to 2007, P fertilizer as monoammonium phosphate (11 % N and 23 % P) at 56 kg P ha^{-1} and K fertilizer as muriate of potash (60 % K) at 48 kg K ha^{-1} were banded to a depth of 5 cm to all crops. The rates for P and K fertilizers were similar to all crops because soil tests prior to crop planting in the spring of each year showed identical levels of P and K in all treatments. Soil NO_3–N levels, however, varied among crops and years. As a result, soil NO_3–N content to a depth of 60 cm after crop harvest in the autumn of previous year was used to adjust N fertilization rate to each crop. Nitrogen fertilizer as urea (46 % N) [either broadcast or banded (Table 2)] and monoammonium phosphate (banded) was applied at 101 kg N ha^{-1} for spring wheat, 67 kg N ha^{-1} for barley hay, and 78 kg N ha^{-1} for corn. Pea received 6 kg N ha^{-1} from monoammonium phosphate. Because no irrigation was applied and leaching of fertilizer, especially N, is minimal in the dryland cropping systems, all fertilizers were applied at the same time during planting. Spring wheat (cv. Reeder) and pea (cv. Majoret) were planted from early April to early May and barley hay (cv. Haybet) was planted in late April (Table 2) with a no-till drill at a spacing of 20.3 cm. Corn (cv. 39T67-RR) was planted in early to mid May at a spacing of 76 cm in 2004 and 61 cm from 2005 to 2007. Growing season weeds were controlled with selective post-emergence herbicides appropriate for each crop. Contact herbicides were applied at preplanting and postharvest. In late June or early July, aboveground biomass of barley (Zadoks scale Z59) was harvested for hay with a self-propelled mower-conditioner and round baler after determining dry yield from two 0.5 m^2 plots at 60 °C for 3 days. In August, total aboveground biomass (stems, leaves, and grains) yield of spring wheat (Z92) and pea (Z75) was determined from two 0.5 m^2 areas outside yield rows after determining dry yields as above and grain yield (at 60 °C) was determined by harvesting grains from a swath of 1.5 m × 12.0 m using a combine harvester. In October, corn biomass and grain yields (Z95) were determined from areas as described above. Biomass (stems and leaves) yield of spring wheat, pea, and corn was determined by deducting grain yield from total aboveground biomass. During grain harvest with combine harvester, biomass (stems and leaves) of spring wheat, pea, and corn were returned to the soil.

Surface residue and soil sample collection and analysis

In November 2007, a month after biomass was returned to the soil, and in April 2008, soil surface residue samples were collected from five 30 cm × 30 cm areas randomly in the central rows of the plot, composited, washed with water to remove soil, and dried in the oven at 60 °C for 7 days to obtain dry matter weight. Samples were ground to pass a 1 mm screen to determine N concentration. After removing the residue, soil samples were collected with a hand probe (5 cm inside diameter) from the 0–20 cm depth from five places in the central rows of the plot. These were separated into 0–5, 5–10, and 10–20 cm depth increments, composited within a depth, air-dried, ground, and sieved to 2 mm for determining N fractions. Surface residue and soil samples were collected at the same time in November 2007 and April 2008 to observe changes in N storage in the residue and soil during the same period as affected by management practices. Because of the difficulty in getting undisturbed soil due to low soil water content, only one additional core (5 cm inside diameter) containing undisturbed sample was collected from each depth in November 2007 and April 2008 to determine bulk density by dividing the mass of the oven-dried (105 °C) soil by the volume of the core. Since bulk density was not influenced by treatments, time of sampling, and interactions, average values of 1.34, 1.36, and 1.49 Mg m^{-3} at 0–5, 5–10, and 10–20 cm were used to convert concentrations (g kg^{-1}) of soil N fractions to contents (Mg ha^{-1} or kg ha^{-1}).

Nitrogen concentration (g N kg^{-1} plant dry weight) in crop grain, biomass (stems + leaves), and surface residue was determined by dry combustion using a high induction furnace C and N analyzer (LECO, St. Joseph, MI). Nitrogen content (kg N ha^{-1}) in them was calculated by multiplying their dry matter weight by N concentration. The STN concentration (g N kg^{-1} soil) in soil samples was determined by using the C and N analyzer as above after grinding the sample to <0.1 mm. For determining PON, 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 dried at 50 °C for 3–4 days and total N concentration was determined by using the analyzer as described above. The PON concentration was determined by the difference between STN in 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 modified 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 days. At 10 days, 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 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 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 days 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 using a correction factor of 2.44 (Voroney and Paul, 1984). The NH_4–N and NO_3–N concentrations determined in the nonfumigated-nonincubated samples were used as available fractions of N.

The contents (Mg N ha^{-1} or kg N ha^{-1}) of STN, PON, PNM, MBN, NH_4–N, and NO_3–N at individual depth increments were calculated by multiplying their concentrations (g N kg^{-1} or mg N kg^{-1}) by bulk density and thickness of the soil layer. The total contents at 0–20 cm were determined by summing the contents from individual depths.

Data analysis

Data for crop grain and biomass N, surface residue N, and soil N fractions at each depth were analyzed using the MIXED procedure of SAS, with year considered as the repeated measure variable (Littell et al. 1996). Tillage, crop rotation, and cultural practice were considered as fixed effects and replication and tillage × replication as random effects. Since each phase of crop rotation was present in every year, data for phases were averaged within a rotation and used for a crop rotation for the analysis. Means were separated by using the least square means test when treatments and interactions were significant (Littell et al. 1996). Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

Results

Crop biomass and soil surface residue nitrogen

Crop biomass N was significant for year ($P < 0.001$) and crop rotation × year interaction ($P < 0.05$). Averaged across tillage and cultural practices, biomass N was greater in W-B-C-P than in CW in 2005 (Table 3). Averaged across treatments, biomass N was greater in 2004 and 2006 than in 2005 and 2007.

Soil surface residue N was significant for tillage ($P < 0.05$), year ($P < 0.001$), and tillage × cultural practice interaction ($P < 0.05$). Averaged across crop rotations and years, surface residue N was greater in

Table 3 Effect of crop rotation on crop biomass (stems and leaves) N content from 2004 to 2007

Years	Crop rotation[a] (kg N ha^{-1})		
	CW	W-B-C-P	Mean
2004	78.8a[b]A[c]	89.7aA	84.3a
2005	39.7bB	57.1bA	48.4b
2006	79.2aA	66.9bA	73.1a
2007	52.1bA	60.7bA	56.4b
Mean	62.5A	68.6A	

[a] Crop rotations are CW, continuous spring wheat; and W-B-C-P, spring wheat-barley hay-corn-pea

[b] Numbers followed by different lowercase letters within a column (among years) are significantly different at $P \leq 0.05$ by the least square means test

[c] Numbers followed by different uppercase letters within a row (between crop rotations) are significantly different at $P \leq 0.05$ by the least square means test

Table 4 Effects of tillage and cultural practice on soil surface residue N content in 2007 and 2008

Tillage[a]	Cultural practice[b]	Years	Soil surface residue N (kg N ha^{-1})
NT	Regular		34.8
	Ecological		33.2
CT	Regular		23.0
	Ecological		28.7
LSD (0.05)			10.1
Means			
NT			34.0a[c]
CT			25.9b
		2007	38.9a
		2008	23.2b

[a] Tillage practices are CT, conventional tillage; and NT, no-tillage

[b] See Table 2 for the description of cultural practices

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

[d] Not significant

NT with the regular and ecological practices than in CT with the regular practice (Table 4). Averaged across crop rotations, cultural practices, and years, surface residue N was 31 % greater in NT than in CT. Averaged across treatments, surface residue N declined by 40 % from autumn 2007 to spring 2008.

Soil total and particulate organic nitrogen

The STN content at 10–20 and 0–20 cm was significant for the cultural practice ($P < 0.001$) and STN and PON contents at all depths were significant for the year ($P < 0.05$). The tillage × cultural practice interaction was significant for STN at 10–20 and 0–20 cm ($P < 0.05$). Similarly, the crop rotation × cultural practice interaction was significant for PON at 0–20 cm ($P < 0.05$).

Averaged across crop rotations and years, STN at 10–20 and 0–20 cm was greater in NT with the regular practice than in NT and CT with the ecological practice (Table 5). Averaged across tillage, crop rotations, and years, STN at 10–20 and 0–20 cm was greater in the regular than in the ecological practice. Averaged across treatments, STN at all depths declined from 10 to 12 % from autumn 2007 to spring 2008. Similarly, PON at 0–20 cm, averaged across tillage and years, was greater in CW with the regular practice or W-B-C-P with the ecological practice than in CW with the ecological practice (Table 6). Averaged across treatments, PON at all depths declined from 14 to 27 % from autumn 2007 to spring 2008.

Soil microbial biomass nitrogen and potential nitrogen mineralization

The MBN content significantly varied between cultural practices at 5–10 cm ($P < 0.05$) and between years at all depths ($P < 0.01$). Interaction was significant for tillage × cultural practice at 10–20 and 0–20 cm ($P < 0.05$). Averaged across crop rotations and years, MBN at 10–20 and 0–20 cm was greater in NT with the regular practice than in CT with the ecological practice (Table 7). Averaged across tillage, crop rotations, and years, MBN at 5–10 cm was greater in the regular than in the ecological practice. Averaged across treatments, MBN at all depths declined from 33 to 48 % from autumn 2007 to spring 2008.

Similar to MBN, PNM content significantly varied between cultural practices at 5–10 cm ($P < 0.05$) and between years at 0–5 and 0–20 cm ($P < 0.05$). Averaged across tillage, crop rotations, and years, PNM at 5–10 cm was greater in the regular than in the ecological practice (Table 8). In contrast to other N fractions, PNM, averaged across treatments, increased

Table 5 Effects of tillage and cultural practice on soil total N (STN) content at the 0–20 cm depth in 2007 and 2008

Tillage[a]	Cultural practice[b]	Years	STN content (Mg N ha^{-1})			
			0–5 cm	5–10 cm	10–20 cm	0–20 cm
NT	Regular		0.97	0.86	1.77	3.60
	Ecological		1.00	0.86	1.66	3.52
CT	Regular		0.98	0.86	1.72	3.56
	Ecological		0.95	0.82	1.66	3.43
LSD (0.05)			NS[c]	NS	0.10	0.13
Mean						
	Regular		0.97a[d]	0.86a	1.75a	3.58a
	Ecological		0.98a	0.84a	1.66b	3.48b
		2007	1.03a	0.90a	1.80a	3.73a
		2008	0.92b	0.80b	1.60b	3.32b

[a] Tillage practices are CT, conventional tillage; and NT, no-tillage

[b] See Table 2 for the description of cultural practices

[c] Not significant

[d] Numbers followed by different letters within a column in either cultural practice or year are significantly different at $P \leq 0.05$ by the least square means test

Table 6 Effects of crop rotation and cultural practice on soil particulate organic N (PON) content at the 0–20 cm depth in 2007 and 2008

Crop rotation[a]	Cultural practice[b]	Years	PON content (Mg N ha^{-1})			
			0–5 cm	5–10 cm	10–20 cm	0–20 cm
CW	Regular		0.20	0.17	0.28	0.65
	Ecological		0.19	0.12	0.26	0.57
W-B-C-P	Regular		0.21	0.13	0.26	0.60
	Ecological		0.22	0.14	0.29	0.65
LSD (0.05)			NS[c]	NS	NS	0.06
Mean						
		2007	0.23a[d]	0.15a	0.29a	0.67a
		2008	0.18b	0.11b	0.25b	0.54b

[a] Crop rotations are CW, continuous spring wheat; and W-B-C-P, spring wheat-barley hay-corn-pea

[b] See Table 2 for the description of cultural practices

[c] Not significant

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

from 43 % at 0–20 cm to 48 % at 0–5 cm from autumn 2007 to spring 2008.

Soil ammonium- and nitrate-nitrogen

Soil NH_4–N content at all depths significantly varied between years ($P < 0.001$) (Table 9). Interactions were significant for tillage × cultural practice (0–5 cm) ($P < 0.05$), tillage × crop rotation × year (10–20 cm) ($P < 0.05$), cultural practice × year (5–10 cm) ($P < 0.05$), and tillage × crop rotation × cultural practice × year (5–10, 10–20, and 0–20 cm) ($P < 0.05$). Similarly, interactions were significant for soil NO_3–N content for crop rotation × cultural practice (5–10 cm) ($P < 0.05$), tillage × cultural practice × year (10–20 cm) ($P < 0.05$), and

Table 7 Effects of tillage and cultural practice on soil microbial biomass N (MBN) contents at the 0–20 cm depth in 2007 and 2008

Tillage[a]	Cultural practice[b]	Years	MBN content (kg N ha^{-1})			
			0–5 cm	5–10 cm	10–20 cm	0–20 cm
NT	Regular		34.5	15.1	22.1	71.7
	Ecological		32.3	11.9	19.6	63.8
CT	Regular		26.6	15.0	18.7	60.3
	Ecological		27.5	10.2	13.1	50.8
LSD (0.05)			NS[c]	NS	9.0	13.5
Mean						
	Regular		30.6a	15.1a	20.4a	66.1a
	Ecological		29.9a	11.1b	16.4a	57.4a
		2007	39.9a	15.6a	26.0a	81.5a
		2008	20.6b	10.5b	16.0b	47.1b

[a] Tillage practices are CT, conventional tillage; and NT, no-tillage

[b] See Table 2 for the description of cultural practices

[c] Not significant

[d] Numbers followed by different letters within a column in either cultural practice or year are significantly different at $P \leq 0.05$ by the least square means test

Table 8 Effect of cultural practice on soil potential N mineralization (PNM) content at the 0–20 cm depth in 2007 and 2008

Cultural practice[a]	Years	PNM content (kg N ha^{-1})			
		0–5 cm	5–10 cm	10–20 cm	0–20 cm
Regular		5.4a[b]	3.6a	2.8a	11.8a
Ecological		6.0a	2.8b	2.4a	11.2a
	2007	4.6b	2.9a	2.1a	9.6b
	2008	6.8a	3.9a	3.0a	13.7a

[a] See Table 2 for the description of cultural practices

[b] Numbers followed by different letters within a column in either cultural practice or year are significantly different at $P \leq 0.05$ by the least square means test

[c] Not significant

tillage × crop rotation × cultural practice × year (10–20 and 0–20 cm) ($P < 0.05$).

The NH_4–N content at 5–10 and 0–20 cm was greater in the regular than in the ecological practice in NT with CW and in CT with W-B-C-P in 2007 (Table 9). At 10–20 cm, NH_4–N content was also greater in the regular than in the ecological practice in NT with CW in 2007 and in CT with CW in 2008. Averaged across crop rotations and years, NH_4–N content at 0–5 cm was greater in CT than in NT in the regular practice. The NH_4–N content at all depths declined from 33 to 54 % from autumn 2007 to spring 2008.

The NO_3–N content at 10–20 and 0–20 cm was greater in the regular than in the ecological practice in CT with W-B-C-P in 2007 (Table 10). Averaged across tillage and years, NO_3–N content at 5–10 cm was greater in W-B-C-P than in CW in the regular practice.

Nitrogen balance

Because of variations in N fertilization rates to crops, N removed in crop grains and hay, and final STN levels, estimated N balance varied among treatments (Table 11). Total soil residual N and N fertilization

Table 9 Effects of tillage, crop rotation, and cultural practice on soil NH_4–N content at the 0–20 cm depth in 2007 and 2008

Years	Tillage[a]	Crop rotation[b]	Cultural practice[c]	NH_4–N content (kg N ha^{-1})			
				0–5 (cm)	5–10 (cm)	10–20 (cm)	0–20 (cm)
2007	NT	CW	Regular	3.6	2.7	7.1	13.4
			Ecological	2.9	1.9	5.3	10.1
		W-B-C-P	Regular	2.5	2.2	4.6	9.3
			Ecological	2.8	2.3	4.6	9.7
	CT	CW	Regular	3.7	2.8	5.0	11.5
			Ecological	4.3	3.4	5.3	13.0
		W-B-C-P	Regular	5.2	3.2	6.3	14.7
			Ecological	2.7	2.5	5.1	10.3
2008	NT	CW	Regular	1.3	1.3	2.8	5.4
			Ecological	1.4	1.7	2.4	5.5
		W-B-C-P	Regular	1.5	1.4	2.8	5.7
			Ecological	1.7	1.6	2.9	6.2
	CT	CW	Regular	1.8	1.4	4.3	7.5
			Ecological	1.8	1.7	2.8	6.3
		W-B-C-P	Regular	2.2	1.8	2.9	6.9
			Ecological	1.5	2.3	3.2	7.0
LSD (0.05)				NS[d]	0.6	1.3	2.8
Mean							
2007				3.5a[e]	2.6a	5.4a	11.5a
2008				1.6b	1.7b	3.0b	6.3b

[a] Tillage practices are CT, conventional tillage; and NT, no-tillage

[b] Crop rotations are CW, continuous spring wheat; and W-B-C-P, spring wheat-barley hay-corn-pea

[c] See Table 2 for the description of cultural practices

[d] Not significant

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

rate was higher in CW than in W-B-C-P, because spring wheat received higher N rate than other crops in the rotation due to higher yield goal. In contrast, total N removed in grains and hay was greater in W-B-C-P than in CW, because N was removed in barley hay and spring wheat, corn, and pea grains in W-B-C-P as opposed to only spring wheat grain in CW. Both soil surface residue N and final STN levels were greater in NT with the regular practice than in other treatments (Tables 4, 5).

Estimated N balance was calculated by deducting the sum of initial STN content in 2004 and total N fertilization rates to crops and residual soil inorganic N from 2004 to 2007 from the sum of total N removed in grains and hay from 2004 to 2007, soil surface residue N, and final STN levels in 2007 and 2008 (Table 11). Because of the different levels of surface residue and soil total N in 2007 and 2008, separate N balance was calculated for 2007 and 2008. In 2007, N balance was greater in the regular than in the ecological practice in NT and CT with CW and in CT with W-B-C-P. In 2008, N balance was greater in the regular than in the ecological practice in NT with W-B-C-P and in CT with CW but was greater in the ecological than in the regular practice in NT with CW. Averaged across tillage, crop rotations, and years, N balance was greater in the regular than in the ecological practice. Averaged across tillage, cultural practices, and years, N balance was greater in W-B-C-P than in CW. From autumn 2007 to spring 2008, N balance declined in all treatments. The reduction in N balance during this period was greater in the regular (721 kg N ha^{-1}) than in the ecological practice (113 kg N ha^{-1}) in CW but was greater in the

Table 10 Effects of tillage, crop rotation, and cultural practice on soil NO_3–N content at the 0–20 cm depth in 2007 and 2008

Years	Tillage[a]	Crop rotation[b]	Cultural practice[c]	NO_3–N content (kg N ha^{-1})			
				0–5 (cm)	5–10 (cm)	10–20 (cm)	0–20 (cm)
2007	NT	CW	Regular	3.5	1.7	7.4	12.6
			Ecological	3.6	1.3	2.3	7.2
		W-B-C-P	Regular	5.2	1.6	4.7	11.5
			Ecological	4.9	3.6	7.6	16.1
	CT	CW	Regular	2.9	0.9	2.1	5.9
			Ecological	5.2	2.9	5.8	13.9
		W-B-C-P	Regular	12.5	10.0	15.3	37.8
			Ecological	3.9	1.5	2.4	7.8
2008	NT	CW	Regular	5.8	2.9	4.5	13.2
			Ecological	5.2	4.7	7.3	17.2
		W-B-C-P	Regular	6.0	3.4	6.0	15.4
			Ecological	6.2	4.2	4.8	15.2
	CT	CW	Regular	8.4	2.9	4.0	15.3
			Ecological	8.3	5.6	5.9	19.8
		W-B-C-P	Regular	8.3	5.3	5.4	19.0
			Ecological	4.5	4.6	6.0	15.1
LSD (0.05)				NS[d]	NS	10.2	23.4

[a] Tillage practices are CT, conventional tillage; and NT, no-tillage

[b] Crop rotations are CW, continuous spring wheat; and W-B-C-P, spring wheat-barley hay-corn-pea

[c] See Table 2 for the description of cultural practices

[d] Not significant

ecological (503 kg N ha^{-1}) than in the regular practice (299 kg N ha^{-1}) in W-B-C-P in NT.

Discussion

The greater biomass N in W-B-C-P than in CW in 2005 (Table 3) was due to increased N contribution by corn as a result of higher yield than other crops. Biomass N, however, was lower in 2005 and 2007 than in other years, probably due to poor distribution of precipitation. Total monthly precipitation was 115 mm in June but only 2 mm in September in 2005 compared with the normal (68-year average) amounts of 72 mm and 34 mm in these months, respectively (Table 1). Similarly, lower total monthly precipitation of 8 mm in August and growing season of 253 mm compared with the normal amounts of 37 and 311 mm, respectively, probably resulted in lower biomass N in 2007. Variations in monthly and seasonal precipitation among years can influence dryland crop yield and N uptake (Halvorson et al. 2002; Sainju et al. 2009b). Tillage and cultural practice did not influence biomass N, a case similar to that observed by several researchers (Halvorson et al. 2002; Sainju et al. 2009a). Variations in crop biomass N returned to the soil among treatments and years can influence surface residue N and soil N fractions, as shown below.

Higher surface residue N in NT with the regular and ecological practices than in CT with the regular practice (Table 4) was probably a result of reduced mineralization of N from crop residue due to its placement at the soil surface. Reduced contact of soil microorganisms with crop residue reduces mineralization of residue N in NT (Bowman et al. 1999; Sainju et al. 2009a). The decline in surface residue N from autumn 2007 to spring 2008 suggests that residue N mineralization can occur even during the harsh winter season in the northern Great Plains.

The greater STN at 10–20 and 0–20 cm in NT with the regular practice than in other treatments (Table 5) was likely the results of reduced soil disturbance and shorter fallow period, especially at the subsurface soil

Table 11 Effects of tillage, crop rotation, and cultural practice on the estimated N balance as a result of N fertilization to crops, N removal in grains and hay from 2004 to 2007, surface residue N in 2007 and 2008, and soil total N (STN) content at the 0–20 cm depth at the beginning (2004) and end (2007 and 2008) of the experiment

Tillage[a]	Crop rotation[b]	Cultural practice[c]	Initial STN (A) (kg N ha^{-1})	Total N fertilization and soil inorganic N(B) (kg N ha^{-1})	Total N removed in grains and hay (C) (kg N ha^{-1})	Soil surface residue N		Final STN		Estimated N balance[d]	
						2007 (D) (kg N ha^{-1})	2008 (E) (kg N ha^{-1})	2007 (F) (kg N ha^{-1})	2008 (G) (kg N ha^{-1})	2007 (H) (kg N ha^{-1})	2008 (I) (kg N ha^{-1})
NT	CW	R	3,087	404	121	33	26	3,870	3,156	533	−188
		E	3,087	404	130	43	27	3,650	3,553	332	219
	W-B-C-P	R	3,087	252	220	37	28	3,781	3,491	699	400
		E	3,087	252	210	43	32	3,678	3,186	592	89
CT	CW	R	3,087	404	124	34	10	3,793	3,330	460	−27
		E	3,087	404	95	30	17	3,612	3,158	246	−221
	W-B-C-P	R	3,087	252	165	30	20	3,812	3,375	669	221
		E	3,087	252	204	48	26	3,658	3,273	571	164
LSD (0.05)			–	–	90	NS[e]	NS	NS	NS	160	130

[a] Tillage practices are CT, conventional tillage; and NT, no-tillage

[b] Crop rotations are CW, continuous spring wheat; and W-B-C-P, spring wheat-barley hay-corn-pea

[c] Cultural practices are E, ecological and R, regular. See Table 2 for the description of cultural practices

[d] Estimated N balance for 2007 is H = C + D + F − A − B and for 2008 is I = C + E + G − A − B

[e] Not significant

layer. Increased N mineralization due to residue incorporation to a greater depth and soil disturbance, followed by longer duration of fallow probably reduced STN in CT with the ecological practice. Increased STN with NT compared to CT and with shorter than with longer fallow period under dryland cropping systems in the northern Great Plains have been reported by several researchers (Wienhold and Halvorson, 1998; Sainju et al. 2009a). The decline in STN from autumn 2007 to spring 2008 suggests that N is lost from the soil during the winter probably due to leaching, volatilization, and denitrification as a result of continuous N mineralization.

The STN content at 0–20 cm before the initiation of the experiment in 2004 was 3.09 Mg N ha^{-1} (0.78 Mg N ha^{-1} at 0–5 cm + 2.31 Mg N ha^{-1} at 5–20 cm). This means that STN increased by 0.34 Mg N ha^{-1} (or 65 kg N ha^{-1} $year^{-1}$) in CT with the ecological practice to 0.51 Mg N ha^{-1} (or 102 kg N ha^{-1} $year^{-1}$) in NT with the regular practice. This shows that, although all treatments increased soil N storage, NT with the regular practice had greater N storage rate than other treatments. Sainju et al. (2009a) reported that NT with continuous cropping increased dryland soil N storage by 46 kg N ha^{-1} $year^{-1}$ compared with CT with crop-fallow in eastern Montana.

The greater PON in the regular than in the ecological practice in CW (Table 6) could be a result of either due to difference in C/N ratio of crop residue or to shorter duration of N mineralization from coarse soil organic matter. In CW, C/N ratio of spring wheat biomass was slightly higher in the regular (43.5) than in the ecological practice (41.9). This could result in increased retention of N in coarse organic matter in the regular practice, since residue with higher C/N ratio mineralizes slowly (Kuo et al. 1997). As with STN, increased mineralization of coarse organic matter due to longer fallow period could have reduced PON in the ecological practice, especially in CW. The decline in PON at all depths from autumn 2007 to spring 2008 shows that, like STN, continuous mineralization probably reduced N in coarse organic matter. Since the percentage decline during this period was higher in PON than in STN, mineralization of soil organic N can reduce N more in the coarse fraction than in whole soil organic matter, a case similar to that observed by several researchers (Cambardella and Elliott 1992; Franzluebbers et al. 1995; Sainju and Lenssen 2011).

The greater MBN at 10–20 and 0–20 cm in NT with the regular practice (Table 7) was probably a result of reduced soil disturbance, followed by shorter duration of fallow, a case similar to that observed for STN. Several researchers (Franzluebbers et al. 1995; Doyle et al. 2004) have also reported greater MBN in NT than in CT. Similarly, the decline in MBN at all depths from autumn 2007 to spring 2008 was probably a result of reduced availability of N substrate due to increased N mineralization.

In contrast to MBN, increased PNM from autumn 2007 to spring 2008 (Table 8) was probably a result of increased N mineralization of crop residue and soil organic N during the winter. The percentage increase in PNM among treatments was similar to percentage decrease in MBN (Table 7), suggesting that N mineralization and immobilization are probably occurring at the same rates during this period in the northern Great Plains. The percentage changes in these fractions were, however, greater than those in STN and PON, suggesting that MBN and PNM can be more reliable indicators of changes in soil N storage than PON and STN. Greater N substrate availability due to higher STN and PON and shorter duration of fallow period probably increased PNM at 5–10 cm in the regular than in the ecological practice.

The greater NH_4–N and NO_3–N contents in the regular than in ecological practice (Tables 9, 10) were probably due to increased levels of active and slow N fractions (MBN, PNM, PON, and STN), as stated above. Increases were especially noted in CT with W-B-C-P, especially following corn, in 2007. Greater soil disturbance and residue incorporation to a greater depth could have increased N mineralization, thereby increasing NH_4–N and NO_3–N contents in CT compared to NT, a case similar to reported by various researchers (Bronson et al. 2001; Zibilske et al. 2002). Reduce N uptake by crops, especially corn (Table 3), due to below-average precipitation from July to October (Table 1) also probably increased soil NH_4–N and NO_3–N in W-B-C-P in 2007. The presence of legumes, such as pea, with higher N concentration in the diversified crop rotation, also could have increased NH_4–N and NO_3–N contents in W-B-C-P than in CW (Heichel and Barnes 1984, Sainju et al. 2009a). While NH_4–N content decreased from autumn 2007 to spring 2008 as STN, PON, and MBN declined, NO_3–N content did not decline during the same period. This is because PNM increased, suggesting that increased N mineralization during the winter probably maintained NO_3–N level from autumn to spring. It also could be possible that N leaching during the winter is minimum, thereby maintaining NO_3–N level from autumn to the following spring, since the ground is frozen for most of the time during this period in the northern Great Plains (Aase and Siddoway 1982). This shows that soil NO_3–N test on samples collected after crop harvest in the autumn can be used to adjust N fertilization rates to succeeding crops in the spring under dryland cropping systems in the northern Great Plains. This is especially important in regions with short growing season where limited time available for planting compromises soil N test in the spring. For measuring surface residue N, STN, PON, and MBN, however, residue and soil samples should be collected at the same time of the year because levels of these fractions can vary from one season to other due to continued mineralization.

The greater N balance in the regular than in the ecological practice in 2007 (Table 11) may be a result of greater STN level (Table 5). The reverse trend in NT with CW in 2008, however, resulted in a lower reduction in N balance in the ecological than in regular practice from autumn 2007 to spring 2008. This was probably due to differences in N mineralization rates among treatments, where increased mineralization can result in increased N loss through leaching, volatilization, and denitrification in the winter. Similarly, greater N balance in W-B-C-P than in CW in 2007 and 2008 may be a result of greater N removed in grains and hay, followed by inclusion of legumes, such as pea, in the crop rotation that supply a greater amount of N to the soil compared with nonlegumes. Sainju and Lenssen (2011) also found that N balance was greater with legumes alone or legume-nonlegume rotations than with nonlegumes. The results suggest that diversified crop rotation and reducing the length of the fallow period by using the regular cultural practice can increase N cycling compared with monocropping and the ecological practice. Because of continuous N mineralization, substantial amounts of N (113–721 kg N ha^{-1}) can be lost even during the winter under dryland cropping systems in the northern Great Plains.

Conclusions

As hypothesized, no-tillage with the regular cultural practice increased surface residue and soil N storage and estimated N balance but conventional tillage with diversified crop rotation increased N mineralization and availability. Based on these results, no-tillage with the regular cultural practice can be used as a management option to increase N storage in the surface residue and soil and therefore N cycling under dryland cropping systems in the northern Great Plains, USA. However, the management practice may reduce N mineralization and availability in the short-term. Regardless of the management practices, soil NO_3–N test done on autumn samples can be used to adjust N fertilization rates to succeeding crops in the spring due to continuous N mineralization in the winter. For measuring surface residue and soil N storage and N balance, however, residue and soil samples should be collected at the same time of the year.

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