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Carbon Sequestration in Dryland Soils and Plant Residue as Influenced by Tillage and Crop Rotation

Upendra M. Sainju,* Andrew Lenssen, Thecan Caesar-Thonthat, and Jed Waddell

ABSTRACT

Long-term use of conventional tillage and wheat (*Triticum aestivum* L.)–fallow systems in the northern Great Plains have resulted in low soil organic carbon (SOC) levels. We examined the effects of two tillage practices [conventional till (CT) and no-till (NT)], five crop rotations [continuous spring wheat (CW), spring wheat–fallow (W–F), spring wheat–lentil (*Lens culinaris* Medic.) (W–L), spring wheat–spring wheat–fallow (W–W–F), and spring wheat–pea (*Pisum sativum* L.)–fallow (W–P–F)], and Conservation Reserve Program (CRP) planting on plant C input, SOC, and particulate organic carbon (POC). A field experiment was conducted in a mixture of Scobey clay loam (fine-loamy, mixed, Aridic Argiborolls) and Kevin clay loam (fine, montmorillonitic, Aridic Argiborolls) from 1998 to 2003 in Havre, MT. Total plant biomass returned to the soil from 1998 to 2003 was greater in CW (15.5 Mg ha^{-1}) than in other rotations. Residue cover, amount, and C content in 2004 were 33 to 86% greater in NT than in CT and greater in CRP than in crop rotations. Residue amount (2.47 Mg ha^{-1}) and C content (0.96 Mg ha^{-1}) were greater in NT with CW than in other treatments, except in CT with CRP and W–F and in NT with CRP and W–W–F. The SOC at the 0- to 5-cm depth was 23% greater in NT (6.4 Mg ha^{-1}) than in CT. The POC was not influenced by tillage and crop rotation, but POC to SOC ratio at the 0- to 20-cm depth was greater in NT with W–L (369 g kg^{-1} SOC) than in CT with CW, W–F, and W–L. From 1998 to 2003, SOC at the 0- to 20-cm depth decreased by 4% in CT but increased by 3% in NT. Carbon can be sequestered in dryland soils and plant residue in areas previously under CRP using reduced tillage and increased cropping intensity, such as NT with CW, compared with traditional practice, such as CT with W–F system, and the content can be similar to that in CRP planting.

Drylands in the northern Great Plains have lost 30 to 50% of their original soil organic carbon (SOC) levels during the last 50 to 100 yr due to continuous cultivation and summer fallowing (Haas et al., 1957; Campbell and Souster, 1982; Mann, 1985; Peterson et al., 1998). While cultivation is done to prepare seed beds for planting crops and controlling weeds, fallowing is done to increase soil water storage and production of succeeding crops (Eck and Jones, 1992; Jones and Popham, 1997). Intensive tillage increases the oxidation of SOC (Follett and Schimel, 1989) and fallowing increases its loss by reducing the amount of plant residue returned to the soil (Schomberg and Jones, 1999; West and Post, 2002). Increased soil moisture and temperature during fallowing can also accelerate mineralization of SOC (Haas et al., 1974, p. 2–35). Soil is vulnerable to wind erosion during fallow, which further increases its loss (Haas et al., 1974, p. 2–35; Halvorson et al., 2002b).

Improved soil and crop management practices that reduce tillage intensity and increase the amount of plant residue returned to the soil can increase SOC compared to conventional till (CT) with spring wheat–fallow (W–F) system in drylands of the Great Plains (Halvorson et al., 2002a, 2002b; Sherrod et al., 2003; Allmaras et al., 2004). Halvorson et al. (2002a) observed that, using no-till (NT) with continuous cropping, C sequestration in drylands of the northern Great Plains increased by 233 kg ha^{-1} yr^{-1} compared with a loss of 141 kg ha^{-1} yr^{-1} in CT with crop–fallow system. They pointed out that continued use of crop–fallow system even in NT increased SOC loss. Similarly, Sherrod et al. (2003) reported that increased cropping intensity in NT increased SOC in drylands of the central Great Plains after 12 yr. After analyzing data from long-term experiments in various locations, West and Post (2002) concluded that conversion from CT to NT can sequester an average of 570 $\pm$ 140 kg C ha^{-1} yr^{-1}, reaching equilibrium in 15 to 20 yr, and enhanced crop rotation can sequester 200 $\pm$ 120 kg C ha^{-1} yr^{-1}, reaching equilibrium in 40 to 60 yr. The benefits of increasing SOC lie not only in enhancing soil structure and soil water–nutrient–crop productivity relationships (Bauer and Black, 1994), but also includes the ability of the soil to store atmospheric C, thereby reducing the concentration of greenhouse gases (Janzen et al., 1999; Lal et al., 1998, 1999).

Because of limited moisture and growing season, crop yields and biomass production are often lower in the Great Plains compared with subhumid regions (Halvorson et al., 2002a). As a result, the amount of crop residue returned to the soil is also lower, thereby taking a longer time to enrich SOC (Halvorson et al., 2002a; Sherrod et al., 2003). Halvorson et al. (2002b) and Ortega et al. (2002) did not observe significant increases in SOC between continuous wheat and wheat–fallow in NT system after 4 to 8 yr, but Sherrod et al. (2003) found increases with continuous cropping only after 12 yr. Since crop residue inputs are directly related to difference in SOC among cropping systems (Collins et al., 1992; Campbell et al., 1992; Campbell and Zentner, 1993), and the balance between the amount of residue and its rate of decomposition in the soil as influenced by tillage intensity determines SOC level (Rasmussen et al., 1980; Havlin et al., 1990; Peterson et al., 1998), the combination of increased cropping intensity and reduced tillage can enhance SOC

USDA-ARS, 1500 North Central Avenue, Sidney, MT 59270. Received 21 Apr. 2005. *Corresponding author (usainju@sidney.ars.usda.gov).

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Abbreviations: CRP, Conservation Reserve Program; CT, conventional till; CW, continuous spring wheat; NT, no-till; POC, particulate organic carbon; SOC, soil organic carbon; W–F, spring wheat–fallow; W–L, spring wheat–lentil; W–P–F, spring wheat–pea–fallow; W–W–F, spring wheat–spring wheat–fallow.

level even in semiarid regions (West and Post, 2002; Halvorson et al., 2002b; Peterson et al., 1998).

Little information is available about long-term studies of cropping system and tillage on SOC and particulate organic carbon (POC) in the northern Great Plains. Although information is available for the central Great Plains (Halvorson et al., 2002b; Ortega et al., 2002; Sherrod et al., 2003), it may not be applicable in the northern Great Plains because of difference in temperature, rainfall, and growing degree days. The SOC changes slowly over time, but POC may change rapidly due to difference in crop yield and residue input as a result of differences in cultural practices, year-to-year differences in growing environment, or the amount of fallow period since last residue was returned to the soil (Cambardella and Elliott, 1992; Campbell et al., 1992; Chan, 1997; Bayer et al., 2001). While SOC is regarded as a recalcitrant pool, POC is considered as a dynamic intermediate pool between active and passive fractions of soil organic matter that change rapidly over time due to changes in management practices, such as tillage and recent addition of crop residue (Cambardella and Elliott, 1992; Chan, 1997; Bayer et al., 2001). We hypothesize that NT with increased cropping intensity and decreased fallow period can increase the amount of plant biomass returned to the soil, residue cover, amount, and C content, and SOC and POC. Our objectives were to: (i) examine the influence of 6 yr of tillage and crop rotations on the amount of biomass of wheat, pea, and lentil returned to the soil, residue cover, amount, and C content, and SOC and POC contents at 0- to 5- and 5- to 20-cm depths in drylands of the northern Great Plains; (ii) compare these parameters in crops and Conservation Reserve Program (CRP) planting; and (iii) determine management practices that sequester C in dryland soils and residue better than the traditional CT with W–F system.

MATERIALS AND METHODS

Site Description

The experimental site was located on a private farm (48°48′ N, 110°1′ W, altitude 886 m) about 56 km west-northwest of Havre, MT. Mean monthly temperature ranged from −10°C in January to 21°C in July and August and annual rainfall was 305 mm. The soils have been mapped as a mixture of 55% of Scobey clay loam (fine-loamy mixed Aridic Argiborolls) with 0 to 4% gradient and 45% Kevin clay loam (fine, montmorillonitic Aridic Argiborolls) with 2 to 4% gradient. The soil sampled in April 1998 before the initiation of the experiment had the following properties: 530 g kg^{-1} sand, 210 g kg^{-1} silt, 260 g kg^{-1} clay, 1.31 Mg m^{-3} bulk density, 20.5 Mg ha^{-1} organic C, 2.23 Mg ha^{-1} total N, and 8.3 pH at the 0- to 20-cm depth. The site was under the Conservation Reserve Program from 1986 to 1997 with an undisturbed vegetation of crested wheatgrass [*Agropyron cristatum* (L.) Gaertn] and alfalfa (*Medicago sativa* L.). The vegetation was killed in 1997 by applying glyphosate [*N*-(phosphonomethyl) glycine)] at 0.84 kg a.i. ha^{-1}.

Treatments

The treatments consisted of two tillage practices (CT and NT), five crop rotations with 1-, 2-, and 3-yr rotations, and CRP planting. The 1-yr rotation consisted of continuous spring wheat, 2-yr rotations of spring wheat–fallow and spring wheat–lentil, and 3-yr rotations of spring wheat–spring wheat–fallow and spring wheat–pea–fallow. Each phase of the crop rotation was present in every year. Because the experiment was conducted for 6 yr from 1998 to 2003, the 1-yr rotation completed six cycles, 2-yr rotations three cycles, and 3-yr rotations two cycles. The CRP consisted of a mixture of alfalfa and three grasses consisting of western wheatgrass [*Pascopyron smithii* (Rydb.) A. Love], slender wheatgrass [*Elmus trachycaulus* (Link.) Gould ex Shinners], and green needlegrass [*Nassella viridula* (Trin.) Backworth]. All crops in rotations and plants in CRP were planted in CT and NT. The CT plots were cultivated with standard sweeps and rods to a depth of 10 cm. The NT plots were left undisturbed, except for drilling seeds and fertilizers. The CT plots under CRP were cultivated in 1998 for planting, after which no further tillage was done. The experiment was designed in randomized complete block with a split-plot arrangement of tillage as main plots and crop rotation as subplots. All treatments were replicated three times. Subplot size was 14.6 by 30.4 m.

Crop Management

Before planting crops in April and May of each year from 1998 to 2003, soil samples collected from the 0- to 60-cm depth from each plot in October of the previous year after fall crop harvest were analyzed for NO_3-N content. Based on soil NO_3–N content and spring wheat yield goal of 2350 kg ha^{-1} and 13% protein content, N fertilizer was applied at different rates to various crops for phases of rotations in CT and NT in each year. As a result, the rate of N fertilization for spring wheat in each phase of the rotation in each year varied from 0 to 78 kg N ha^{-1}. Nitrogen was also applied to pea and lentil at 5 to 6 kg N ha^{-1} while applying P from monoammonium phosphate (11% N, 23% P) in each year, because it was the only P fertilizer available to satisfy P requirement for crops. Nitrogen was applied from urea (46% N) and monoammonium phosphate. Per Montana State University recommendations, P (from monoammonium phosphate) was applied at 56 kg ha^{-1} and K (from muriate of potash, 60% K) at 48 kg ha^{-1} to spring wheat, pea, and lentil every year. All fertilizers were banded to a depth of 5 to 7 cm with a single-pass ConservaPak air seeder (ConservaPak Seeding Systems, Indian Head, SK, Canada) at planting.

Spring wheat (cv. McNeal in 1998 and 1999, Amidon in 2000, and Scholar from 2001 to 2003) was planted at 60 to 70 kg ha^{-1}, pea (cv. Alfetta in 1998 and 1999 and Majorette from 2000 to 2003) at 161 to 258 kg ha^{-1}, and lentil (cv. Richlea from 1998 to 2002 and Indianhead in 2003) at 45 to 110 kg ha^{-1} in April and May of every year. Spring wheat was planted at a depth of 4 to 5 cm and pea and lentil planted at 3 to 6 cm with a ConservaPak air seeder, depending on the depth of moist soil in each year. Seeds were placed at 2 cm above the depth of the fertilizer in the soil. In CRP, alfalfa, western wheatgrass, slender wheatgrass, and green needlegrass were planted at 2.2 kg ha^{-1} each in April 1998. No fertilizers or herbicides were applied to plants in CRP. Weeds were controlled by applying appropriate herbicides to each crop at preplanting, during crop growth, and at postharvest, except in 1998 and 1999 when CT plots were tilled with sweeps. Similarly, to control weeds, summer fallow plots in CT were tilled with sweeps, while fallow plots in NT were treated with glyphosate at 0.84 kg a.i. ha^{-1}.

Plant and Soil Sample Collection

Before grain harvest in July and August, total crop biomass (grains + stems + leaves) yield in each year was determined from a 30- × 100-cm^2 area within each plot. After separating grains, biomass (stems + leaves) samples were dried in the oven at 55°C for 3 d and dry matter yield was determined. Grain yield was determined (pea in July and spring wheat and lentil in August) by harvesting an area of 1.5 × 30.4 m^2 with a self-propelled combine and yields were converted into dry matter basis after a sample was dried in the oven at 60°C. The remaining stalks containing stems and leaves were returned to the soil. Post-harvest crop residue cover in each plot was determined by using the standard USDA-NRCS point-method of counting 100 points per plot by a 15-m-long string with each point at a 0.15-m spacing.

In March 2004, crop residue amount was determined by collecting residue samples from five 30- × 30-cm^2 areas randomly in the central rows of the plot. Samples were composited, washed with water to separate soil particles, and dried in the oven at 60°C for 3 d to obtain dry matter weight. Samples were ground to 1 mm for C analysis. After removing the residue from the soil surface, soil samples were collected with a hand probe (5-cm i.d.) from the 0- to 20-cm depth from five places in the central rows of the plot, separated into 0- to 5- and 5- to 20-cm depths, and composited within a depth. Samples were air-dried, ground, and sieved to 2 mm for determining C concentration. A separate undisturbed soil core (5-cm i.d.) was taken from 0- to 5- and 5- to 20-cm depths from each plot to determine bulk density (Blake and Hartge, 1986).

Carbon Analysis

Total C concentration in crop residue and soils were determined by using a C and N dry combustion analyzer (LECO, St. Joseph, MI). Soils were pretreated with 5% H_2SO_3 to remove inorganic C (Nelson and Sommers, 1996) before C analysis by dry combustion. For determining POC, 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 0.05-mm sieve (Cambardella and Elliott, 1992). The solution and particles that passed through the sieve were dried at 50°C for 3 to 4 d and organic C concentration was determined by using the analyzer as above. The POC concentration was determined by the difference between organic C in whole soil and that in the particles that passed through the sieve after correcting for the sand content. The contents of SOC and POC at 0- to 5- and 5- to 20-cm depths were calculated by multiplying their concentrations by bulk density and depth. Because bulk density was influenced by tillage but not by crop rotation and its interaction with tillage, bulk density values of 1.24 and 1.32 Mg ha^{-1} for CT and NT, respectively, at the 0- to 5-cm depth and 1.32 and 1.34 Mg ha^{-1} at the 5- to 20-cm depth, averaged across crop rotations, were used for the calculation. The total contents of SOC and POC at the 0- to 20-cm depth were determined by summing the contents at 0- to 5- and 5- to 20-cm depths.

Data Analysis

Data for plant biomass returned to the soil in each year, total biomass, residue cover, amount, and C content, and SOC and POC contents were analyzed using the MIXED procedure of SAS (Littell et al., 1996). Tillage and crop rotation were considered as fixed effects and replication and tillage × replication were considered as random effects. For eliminating the phases of the crop rotation, data were averaged across the phases within a rotation. Means were separated by using the least square means test when treatments and interaction were significant. Statistical significance was evaluated at $P \leq 0.10$, unless otherwise stated.

RESULTS AND DISCUSSION

Crop Biomass Yield

Crop rotation significantly ($P \leq 0.05$) influenced biomass (stems + leaves) yields of spring wheat, pea, and lentil returned to the soil from 1999 to 2003 (Table 1). Biomass yield differed not only between crop rotations but also between years. For example, while biomass, averaged across tillage, was significantly higher in W–F than in other crop rotations in 2001, it was higher in continuous spring wheat (CW) than in other rotations, except in spring wheat–lentil (W–L), in 2002. Similarly, biomass was higher in CW and W–F than in W–L in 1999 and 2003. This could be due to the type of crop rotation and the difference in the amount of moisture available in the soil at the time of planting between treatments. Soil

Table 1. Effects of tillage and crop rotation on biomass (stems + leaves) yield of crops from 1998 to 2003.

Treatment	1998†	1999†	2000	2001	2002	2003	Total	Total‡
	Mg ha^{-1}							
	Tillage§							
CT	5.46a¶	3.84a	2.05a	0.46a	2.18a	1.79a	15.78a	6.48b
NT	5.49a	4.10a	2.37a	0.62a	2.50a	1.96a	17.04a	7.45a
	Crop rotation#							
CRP	–	–	–	–	–	1.84	–	–
CW	5.55	3.27	1.88	0.39	2.73	1.71	15.53	6.71
W–F	2.82	3.01	1.39	0.63	1.24	1.54	10.63	4.80
W–L	5.85	2.09	1.66	0.23	2.25	1.06	13.14	5.02
W–W–F	3.28	3.18	1.30	0.34	1.82	1.38	11.30	4.84
W–P–F	3.53	2.89	1.94	0.40	1.18	1.44	11.39	4.97
LSD (0.10)	–	0.90	0.44	0.21	0.34	0.45	1.75	1.30
	Analysis of variance ($P > F$)							
Tillage (T)	0.988	0.708	0.296	0.260	0.230	0.530	0.204	0.098
Crop rotation (C)	0.289	0.018	<0.001	<0.001	0.005	<0.001	<0.001	<0.001
T × C	0.948	0.987	0.914	0.888	0.289	0.876	0.901	0.644

† Biomass yield for 1998 and 1999 were projected from their grain yield and the average biomass yield to grain yield ratio from 2000 to 2003.
‡ Total biomass yield from 2000 to 2003.
§ CT, conventional till; NT, no-till.
¶ Numbers followed by same letters within a tillage treatment are not significantly different at $P \leq 0.10$ by the least square means test.
# CRP, Conservation Reserve Program (contains alfalfa, green needlegrass, western wheatgrass, and slender wheatgrass); CW, continuous spring wheat; W–F, spring wheat–fallow; W–L, spring wheat–lentil; W–P–F, spring wheat–pea–fallow; W–W–F, spring wheat–spring wheat–fallow.

moisture storage has been reported to be higher following fallow than following wheat in W–F system due to excess water unused by plants during fallow (Farhani et al., 1998; Halvorson et al., 2002a). Total rainfall during the growing season from April to August was 159, 99, 93, 220, 131, and 202 mm in 1999, 2000, 2001, 2002, 2003, and the 87-yr average, respectively. Because of higher rainfall, biomass of wheat, pea, and lentil was higher in 2002 than in 2001. Biomass of wheat, pea, and lentil in 1998 and 1999 was not measured but were predicted from their grain yields and the average biomass yield to grain yield ratio from 2000 to 2003. Since the values in 1998 and 1999 were much larger than those obtained from 2000 to 2003, it may be possible that biomass in 1998 and 1999 was overestimated. Biomass of plants in CRP was measured only in 2003. Tillage did not influence biomass of crops, except for the total biomass from 2000 to 2003 where biomass was higher in NT than in CT.

Total biomass yield of crops returned to the soil from 1998 to 2003, averaged across tillage, was significantly greater in CW and W–L than in other crop rotations (Table 1). When biomass from 1998 and 1999 was omitted, total biomass from 2000 to 2003 was still greater in CW than in other rotations. Increased biomass yield with CW and W–L as compared with other rotations suggests that increased cropping intensity, regardless of tillage, can increase the amount of crop biomass returned to the soil. This is consistent with observations as found by several researchers (Halvorson et al., 2002a, 2002b; Ortega et al., 2002; Sherrod et al., 2003).

Crop Residue Cover, Amount, and Carbon Content

Crop residue cover in 2003 varied between tillage and crop rotations (Table 2). It is not surprising to observe higher residue cover in NT than in CT because residues were accumulated at the soil surface in NT compared to CT where residues were incorporated into the soil. Similarly, residue cover was higher in CRP than in other crop rotations, probably because perennial forages cover much of the soil, even in CT where tillage was discontinued after planting. Residue cover was also higher in W–L than in other rotations, except in CW. This is because the total amount of biomass returned to the soil was higher in CW and W–L than in other rotations (Table 1). Greater residue cover will obviously reduce the potential of soil erosion due to wind and water.

Crop residue amount varied between tillage and crop rotations (Tables 2 and 3), similar to crop residue cover, because residue amount was highly correlated with residue cover ($r = 0.87$, $P \leq 0.001$). The difference in residue amount between crop rotations in CT and NT led to a significant ($P \leq 0.05$) tillage × crop rotation interaction. Although residue amount was higher in CRP, regardless of tillage, it was also higher in W–F in than in other rotations, except in spring wheat–spring wheat–fallow (W–W–F) in CT (Table 3). In NT, residue amount was higher in CW than in other rotations, except in W–W–F. Similarly, residue amount was higher in NT than in CT within CW, W–L, and W–W–F. Since there was no significant tillage × crop rotation interaction in the amount of crop biomass returned to the soil (Table 1), the difference in the residue amount between crop rotations in CT and NT could be either due to variations in the amount of biomass returned to the soil between crop rotations, or to decomposition rates of residue due to tillage. Averaging across the treatments, residue amount was greater in NT than in CT and greater in CRP than in crop rotations (Table 2). The greater amount of residue in NT with CW supports the observations of Halvorson et al. (2002a, 2002b) that reduced tillage and increased cropping intensity increases the amount of soil surface residue. Considering that the amount of residue lost or gained due to actions of wind and water is minimal, the amount of residue left in the soil after 6 yr of total biomass addition accounted for

Table 2. Effects of tillage and crop rotation on crop residue cover, amount, and C content in 2003.

	Residue		Carbon	
Treatment	Cover	Amount	Concentration	Content
	%	Mg ha^{-1}	g kg^{-1}	kg ha^{-1}
		Tillage†		
CT	43b‡	1.06b	372a	394b
NT	57a	1.87a	394a	736a
		Crop rotation§		
CRP	94	2.73	427	1165
CW	60	1.45	365	529
W–F	45	1.80	398	739
W–L	69	0.82	378	329
W–W–F	50	1.69	381	659
W–P–F	41	1.03	370	403
LSD (0.10)	19	0.64	30	272
		Analysis of variance ($P > F$)		
Tillage (T)	0.057	0.064	0.172	0.068
Crop rotation (C)	<0.001	<0.001	0.012	<0.001
T × C	0.784	0.040	0.253	0.050

‡ CT, conventional till; NT, no-till.
‡ Numbers followed by same letters within a tillage treatment are not significantly different at $P \leq 0.10$ by the least square means test.
§ CRP, Conservation Reserve Program (contains alfalfa, green needlegrass, western wheatgrass, and slender wheatgrass); CW, continuous spring wheat; W–F, spring wheat–fallow; W–L, spring wheat–lentil; W–P–F, spring wheat–pea–fallow; W–W–F, spring wheat–spring wheat–fallow.

Table 3. Interacting effects of tillage and crop rotation on crop residue cover, amount, and C content in 2003.

		Residue		Carbon	
Tillage†	Crop rotation‡	Cover	Amount	Concentration	Content
		%	Mg ha^{-1}	g kg^{-1}	kg ha^{-1}
CT	CRP	97	2.63	423	1112
	CW	28	0.44	339	149
	W–F	35	2.01	390	830
	W–L	28	0.22	349	73
	W–W–F	43	1.07	370	411
	W–P–F	34	0.67	372	262
NT	CRP	77	2.83	431	1220
	CW	60	2.47	390	963
	W–F	55	1.60	408	647
	W–L	51	1.43	407	585
	W–W–F	57	2.32	392	906
	W–P–F	47	1.39	367	544
	LSD (0.10)	–	0.95	–	281

† CT, conventional till; NT, no-till.
‡ CRP, Conservation Reserve Program (contains alfalfa, green needlegrass, western wheatgrass, and slender wheatgrass); CW, continuous spring wheat; W–F, spring wheat–fallow; W–L, spring wheat–lentil; W–P–F, spring wheat–pea–fallow; W–W–F, spring wheat–spring wheat–fallow.

9% in CW, 17% in W–F, 6% in W–L, 15% in W–W–F, and 9% in spring wheat–pea–fallow (W–P–F). Since 2000 kg ha^{-1} surface residue is needed to effectively control soil erosion (Fenster et al., 1977; Fryrear, 1985), NT with CRP, CW, and W–W–F will have increasing potentials to reduce soil erosion (Table 3).

Carbon concentration in the residue was higher in CRP than in other rotations, except in W–F (Table 2). Carbon content in the residue mirrored with residue amount because difference in C concentration due to treatments was small and variation in C content was largely due to variation in residue amount. Because of higher C content, C can be conserved in the residue using NT with CW better than in other tillage and crop rotation treatments. The conservation of C in the residue in NT with CW can be similar to that in CRP.

Soil Carbon

The SOC was significantly ($P \leq 0.10$) influenced by tillage at 0- to 5-cm depth but crop rotation and tillage × crop rotation interaction were not significant (Table 4). Averaged across crop rotations, SOC at the 0- to 5-cm depth was 23% greater in NT than in CT. At 5- to 20- and 0- to 20-cm depths, SOC also tended to be greater in NT than in CT but it was not statistically significant. Our results are consistent with those obtained by Halvorson et al. (2002a, 2002b) who observed greater levels of SOC in NT than in CT at the 0- to 7.6-cm depth but not at the 7.6- to 15.2-cm depth in the northern and central Great Plains after 5 to 12 yr. Although a greater amount of crop residue was returned to the soil in CW than in other rotations, crop rotation did not influence SOC. Halvorson et al. (2002a) found that increased crop biomass residue returned to the soil with continuous corn or wheat–corn–fallow rotation did not increase SOC compared with W–F in NT or CT after 5 yr in the central Great Plains. Similarly, Ortega et al. (2002) reported that SOC was not significantly influenced by crop rotation in NT system after 8 yr in the central Great Plains, even though continuous cropping returned greater biomass residue to the soil than other crop rotations containing fallow. Increased cropping intensity increased biomass residue and SOC only after 12 yr (Sherrod et al., 2003). Tillage probably has a greater influence on SOC than crop rotation. Before the initiation of the experiment, our study site was under CRP for 10 yr but the sites used by Halvorson et al. (2002a, 2002b) were under conventional tillage. However, consistency in results between tillage systems in our study and their studies suggests that plant residue returned to the soil in 6 yr probably does not have much influence on SOC. West and Post (2002) concluded that reducing tillage intensity sequestered more SOC than enhancing crop rotation. Perhaps a longer time than the present 6 yr of study may be needed to observe changes in SOC due to crop rotation in the northern Great Plains.

The baseline soil sample collected in 1998 before the initiation of the experiment contained SOC at 20.5 Mg ha^{-1} at the 0- to 20-cm depth. After 6 yr, SOC was 19.7 Mg ha^{-1} in CT and 21.1 Mg ha^{-1} in NT (Table 4). This indicates that SOC was reduced by 4% in CT but was increased by 3% in NT after 6 yr of tillage. Halvorson et al. (2002b) also observed net gain of 7% SOC in NT with annual cropping system but 8% loss in CT with W–F system at the 0- to 15.2-cm depth after 12 yr in the northern Great Plains. This suggests that C was lost by a rate of 134 kg ha^{-1} yr^{-1} in CT but was gained by 100 kg

Table 4. Effects of tillage and crop rotation on soil organic carbon (SOC) and particulate organic carbon (POC) contents from the 0- to 20-cm depth in 2003.

		SOC content at soil depth (cm)			POC content at soil depth (cm)			POC to SOC ratio at soil depth (cm)		
Tillage†	Crop rotation‡	0–5	5–20	0–20	0–5	5–20	0–20	0–5	5–20	0–20
		Mg ha^{-1}						g kg^{-1} SOC		
CT	CRP	6.0	13.8	19.8	2.2	4.9	7.1	364	351	357
	CW	5.5	13.9	19.4	1.6	4.5	6.1	288	317	310
	W–F	5.1	14.8	19.9	1.8	4.5	6.3	349	304	316
	W–L	5.4	15.0	20.4	1.8	4.4	6.2	326	298	305
	W–W–F	5.0	14.0	19.0	2.0	4.8	6.8	394	344	357
	W–P–F	5.2	14.6	19.7	1.8	5.0	6.9	356	343	347
NT	CRP	6.4	15.9	22.3	1.9	5.5	7.4	304	394	330
	CW	6.5	14.4	20.9	2.4	5.0	7.4	370	345	353
	W–F	5.8	13.6	19.4	2.1	4.9	7.0	357	360	360
	W–L	6.6	14.5	21.0	2.4	5.3	7.8	365	370	369
	W–W–F	6.9	15.1	20.0	2.2	5.1	7.3	340	341	341
	W–P–F	6.2	14.7	20.9	2.1	5.0	7.1	322	333	330
LSD (0.10)		–	–	–	–	–	–	63	38	41
				Means						
CT		5.2b§	14.5a	19.7a	1.9a	4.7a	6.6a	354a	378a	335a
NT		6.4a	14.7a	21.1a	2.2a	5.1a	7.3a	342a	348a	346a
				Analysis of variance ($P > F$)						
Tillage (T)		0.096	0.687	0.300	0.193	0.319	0.198	0.832	0.184	0.253
Crop rotation (C)		0.274	0.962	0.932	0.786	0.875	0.834	0.811	0.967	0.974
T × C		0.228	0.439	0.414	0.160	0.805	0.547	0.010	0.083	0.008

† CT, conventional till; NT, no-till.
‡ CRP, Conservation Reserve Program (contains alfalfa, green needlegrass, western wheatgrass, and slender wheatgrass); CW, continuous spring wheat; W–F, spring wheat–fallow; W–L, spring wheat–lentil; W–P–F, spring wheat–pea–fallow; W–W–F, spring wheat–spring wheat–fallow.
§ Numbers followed by same letters within a tillage treatment are not significantly different at $P \leq 0.10$ by the least square means test.

$ha^{-1} yr^{-1}$ in NT. The rate of C loss was comparable to a value of 141 kg $ha^{-1} yr^{-1}$ with continuous cropping in CT but the rate of gain was lower than 233 kg $ha^{-1} yr^{-1}$ in NT as observed by Halvorson et al. (2002b) in the northern Great Plains. Since our values were averaged across crop rotation while the values obtained by Halvorson et al. (2002b) are for continuous cropping in NT, the lower sequestration rate in NT in our study could be due to the difference in the quantity and quality of residue returned to the soil every year as a result of the difference in cropping systems and land use history before the initiation of the experiment. The annualized amount of residue returned to the soil from annual crop rotation of spring wheat–winter wheat–sunflower was 3.4 Mg $ha^{-1} yr^{-1}$ in the study of Halvorson et al. (2002b) compared to 2.8 Mg $ha^{-1} yr^{-1}$ in our study. Furthermore, the cropping system in their rotation contained only nonlegume species, whereas crops in our system contained both legumes and nonlegumes. Residues of legumes decompose more rapidly than those of nonlegumes, resulting in a lower C sequestration rate (Kuo et al., 1997; Sainju et al., 2003). Because our site was under CRP before the initiation of the experiment, soils could have reached near-saturation point for sequestering C, thereby resulting in lower sequestration capacity during conversion from CRP to crops in NT compared with CT. Agricultural soils, being depleted of a large amount of organic C due to cultivation, have greater potentials to sequester atmospheric CO_2 than grassland soils if left undisturbed by using NT (Lal and Kimble, 1997; Paustian et al., 1997). Also, the difference in soil and environmental conditions and length of study between the locations may influence C sequestration rate. Our length of study was 6 yr compared with 12 yr of Halvorson et al. (2002b), which may have an impact on reaching equilibration in SOC level. Considering that plant biomass residue has 40% C, about 9% of residue C was sequestered as soil C after 6 yr in the drylands of the northern Great Plains. This is lower than the 16% value obtained by Halvorson et al. (2002b) but greater than 3% for sorghum residue in Kansas as reported by Doyle et al. (2004).

The POC was not influenced by tillage and crop rotation and averaged 2.1, 4.9, and 7.0 Mg ha^{-1} at 0- to 5-, 5- to 20- and 0- to 20-cm depths, respectively (Table 4). The proportion of SOC as POC at the 0- to 5-cm depth was greater in CT with W–W–F than in CT with CW and W–L and in NT with CRP and W–P–F. At the 5- to 20-cm depth, the proportion was greater in NT with CRP than in other treatments, except in NT with W–F and W–L. At the 0- to 20-cm depth, the proportion was greater in NT with W–L than in CT with CW, W–F, and W–L. This indicates that proportion of SOC retained as POC varied with tillage, crop rotation, and soil depth. While CT retained more wheat residue as POC compared to SOC at the 0- to 5-cm depth, NT retained more crop residue as POC at the 5- to 20-cm depth. Probably residue quality, quantity, and their different turnover rates at different depths as influenced by tillage may have influenced the proportion of labile and nonlabile pools of soil C.

CONCLUSIONS

Results from this study showed that tillage and crop rotation influenced the amount of crop biomass residue returned to the soil, residue cover, amount, and C content, and SOC after 6 yr in the northern Great Plains. Biomass increased with increasing cropping intensity but varied between years due to difference in the amount of rainfall. Residue cover was greater in NT than in CT and greater in CRP than in crop rotations. Residue amount and C content were greater in NT with CW and W–W–F than in other treatments, except in CT and NT with CRP and in CT with W–F. Similarly, SOC at the 0- to 5-cm depth was greater in NT than in CT but POC was not influenced by tillage and crop rotation. Carbon can be conserved in plant residue and soil in drylands of the northern Great Plains by using NT with continuous cropping and reduced fallow periods. This will not only improve soil productivity but also will reduce soil erosion. The SOC at the 0- to 5-cm depth in NT with continuous cropping can be similar to that in CRP where the content was generally higher than in the cultivated soil. Longer time than the present 6 yr of study, however, may be needed to observe the effects of cropping intensity and crop rotation on SOC in the northern Great Plains.

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