Long-Term Tillage and Cropping Sequence Effects on Dryland Residue and Soil Carbon Fractions

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Long-term management practices are needed to increase dryland C storage and improve soil quality. We evaluated the 21-yr effects of combinations of tillage and cropping sequences on dryland crop biomass (stems + leaves) returned to the soil, residue C, and soil C fractions at the 0- to 20-cm depth in a Dooley sandy loam (fine-loamy, mixed, frigid, Typic Argiborolls) in eastern Montana. Treatments were no-till continuous spring wheat (*Triticum aestivum* L.) (NTCW), spring-tilled continuous spring wheat (STCW), fall- and spring-tilled continuous spring wheat (FSTCW), fall- and spring-tilled spring wheat–barley (*Hordeum vulgare* L.) (1984–1999) followed by spring wheat–pea (*Pisum sativum* L.) (2000–2004) (FSTW-B/P), and spring-tilled spring wheat–fallow (STW-F). Carbon fractions were soil organic C (SOC), soil inorganic C (SIC), particulate organic C (POC), microbial biomass C (MBC), and potential C mineralization (PCM). Mean crop biomass was 53 to 66% greater in NTCW, STCW, FSTCW, and FSTW-B/P than in STW-F. Soil surface residue amount and C content in 2004 were 46 to 60% greater in NTCW and FSTCW than in STW-F. As a result, soil C fractions at 0 to 20 cm were 23 to 141% greater in all other treatments than in STW-F due to increased C input. At 0 to 5 cm, SOC, SIC, POC, and PCM were greater in NTCW than in FSTW-B/P. At 5 to 20 cm, POC was greater in NTCW than in FSTW-B/P and PCM was greater in STCW than in FSTCW. Long-term reduced tillage with continuous nonlegume cropping increased dryland crop biomass, residue and soil C storage, and soil quality by increasing microbial biomass and activities compared with a conventional system such as STW-F.

Abbreviations: FSTCW, fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); MBC, microbial biomass C; NTCW, no-till continuous spring wheat; PCM, potential carbon mineralization; POC, particulate organic carbon; SIC, soil inorganic carbon; SOC, soil organic carbon; STCW, spring-tilled continuous spring wheat; STW-F, spring-tilled spring wheat–fallow.

In the northern Great Plains, traditional farming systems, such as conventional tillage with wheat (*Triticum aestivum* L.)–fallow, have resulted in a decline in soil organic C (SOC) by 30 to 50% of their original levels in the last 50 to 100 yr (Haas et al., 1957; Mann, 1985; Peterson et al., 1998). Intensive tillage increases the oxidation of SOC (Bowman et al., 1999; Schomberg and Jones, 1999) and fallowing increases its loss by reducing the amount of plant residue returned to the soil (Black and Tanaka, 1997; Campbell et al., 2000). Although extending fallow increases soil water storage and crop yields (Eck and Jones, 1992; Aase and Pikul, 1995; Jones and Popham, 1997; Pikul et al., 1997), increased soil water and temperature during fallow can also accelerate mineralization of SOC (Haas et al., 1974, p. 2–35). As a result, the conventional farming system has become inefficient, uneconomical (Aase and Schaefer 1996), and unsustainable partly due to increased dependence of producers on federal aids (Dhuyvetter et al., 1996).

Maintaining or increasing SOC under dryland cropping systems remains a challenge in the northern Great Plains (Aase and Pikul, 1995). This is because crop biomass yields and C inputs are often lower in drylands than in humid regions due to limited precipitation and a shorter growing season. As a result, it often takes more time to enrich SOC (Halvorson et al., 2002a; Sherrod et al., 2003). Improved soil and crop management practices, such as reduced tillage and increased cropping intensity, however, can increase dryland SOC and C fractions compared with conventional practices (Halvorson et al., 2002a; Sherrod et al., 2003; Sainju et al., 2006a, 2007). Halvorson et al. (2002b) observed that no-till with continuous cropping increased C sequestration in the drylands of the northern Great Plains by 233 kg ha^{-1} yr^{-1}, compared with a loss of 141 kg ha^{-1} yr^{-1} in conventional tillage. They pointed out that continued use of a crop–fallow system even under no-till increased SOC loss. Similarly, Sherrod et al. (2003) reported that increased cropping intensity under no-till increased SOC in drylands of the central Great Plains after 12 yr. The use of no-till has allowed producers to increase cropping intensity in the northern Great Plains (Aase and Pikul, 1995; Aase and Schaefer, 1996; Peterson et al., 2001) because no-till conserves surface residues and retains water in the soil profile more than conventional tillage (Farhani et al., 1998). As a result, soil water can be used more efficiently by crops under no-till (Deibert et al., 1986; Aase and Pikul, 1995), which can reduce or eliminate

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summer fallow by growing continuous crops (Farhani et al., 1998; Peterson et al., 2001).

Carbon conservation in soil and crop residues is needed not only to increase C sequestration for C trading and mitigate greenhouse gases, such as CO_2, but also to improve soil quality for economic crop production. Bauer and Black (1994) reported that an increase in SOC content of 580 kg ha^{-1} in the surface 3 cm of soil increased wheat grain yield by 15.6 kg ha^{-1}. Such an increase in crop production with increased C storage was a result of enhanced soil structure and improved soil water–nutrient–crop productivity relationships (Bauer and Black, 1994). The enhanced soil aggregation and crop residue C can also reduce soil erosion, especially in semiarid regions where soil erosion due to the action of wind is greater than in humid regions. Although C sequestration is directed mostly toward increasing SOC, C conserved in the surface residue and stored as soil inorganic C also constitutes an important part of total C sequestration.

To increase soil C sequestration and biological soil quality, a better understanding of soil C cycling is needed. Some of the parameters of soil C cycling are SOC, soil inorganic C (SIC), particulate organic C (POC), microbial biomass C (MBC), and potential C mineralization (PCM). Since SOC has a large pool size and inherent spatial variability, it changes slowly with management practices (Franzluebbers et al., 1995). As a result, measurement of SOC alone does not adequately reflect changes in soil quality and nutrient status (Franzluebbers et al., 1995; Bezdicek et al., 1996). Measurement of the biologically active fractions of SOC that change rapidly with time, such as MBC and PCM, could better reflect changes in soil quality and productivity that alter nutrient dynamics due to immobilization–mineralization (Saffigna et al., 1989; Bremner and Van Kessel, 1992). These fractions can provide an assessment of soil organic matter changes induced by management practices, such as tillage and cropping system (Campbell et al., 1989; Sainju et al., 2006a). Similarly, POC has been considered as an intermediate fraction of SOC between the active and slow fractions that changes rapidly with time due to changes in management practices (Cambardella and Elliott, 1992; Bayer et al., 2001). The POC also provides substrates for microorganisms and influences soil aggregation (Franzluebbers et al., 1999; Six et al., 1999).

Information on the effects of tillage and cropping system on SOC in the northern Great Plains is available (Aase and Pikul, 1995; Pikul et al., 1997); however, little is known about the long-term (>10-yr) effects of tillage and cropping sequence on the active and slow fractions of soil C. Although information is available for the central Great Plains (Halvorson et al., 2002a; Sherrod et al., 2003), it may not be applicable to the northern Great Plains because of differences in temperature, precipitation, and growing degree days. This study provided a unique opportunity to examine the effects of long-term (21-yr) tillage and cropping sequence regimes on dryland C sequestration and soil quality in the northern Great Plains. We hypothesized that reduced tillage frequency with increased cropping intensity would increase soil and surface residue C storage and C fractions compared with the conventional spring-tilled spring wheat–fallow (STW-F) system. Our objectives were to: (i) examine the 21-yr influence of combinations of tillage frequency and cropping sequence on crop biomass (stems + leaves) returned to the soil, surface residue C, and SOC, SIC, POC, PCM, and MBC contents at 0- to 5- and 5- to 20-cm depths in drylands in the northern Great Plains; and (ii) quantify tillage and cropping sequence effects on C conservation in soil and residue.

MATERIALS AND METHODS

Site Description and Treatments

The experiment was started by Aase and Pikul (1995) in 1983. The experimental site is located 11 km north of Culbertson (48°33′ N, 104°50′ W) in eastern Montana. The site is characterized by wide variation in mean monthly air temperature from −8°C in January to 23°C in July and August and an annual precipitation of 340 mm, 70% of which occurs during the growing season (April–August). The soil is a Dooley sandy loam (fine-loamy, mixed, frigid Typic Argiborolls) with 0 to 2% slope. The soil sampled in 1983 before the initiation of the experiment contained 645 g kg^{-1} sand, 185 g kg^{-1} silt, 170 g kg^{-1} clay, and 16.8 Mg ha^{-1} organic C, and had a bulk density of 1.50 Mg m^{-3} and a pH of 6.2 at the 0- to 8-cm depth (Aase and Pikul, 1995).

Details of the experimental treatments and management were described by Aase and Pikul (1995), Pikul and Aase (1995), and Aase and Schaefer (1996). The treatments consisted of no-till continuous spring wheat (NTCW), spring-tilled continuous spring wheat (STCW), fall- and spring-tilled continuous spring wheat (FSTCW), fall- and spring-tilled spring wheat–barley (*Hordeum vulgare* L.) (1984–1999) followed by spring wheat–pea (*Pisum sativum* L.) (2000–2004) (FSTW-B/P), and STW-F. The cropping sequence contained continuous spring wheat and 2-yr sequences of spring wheat–barley followed by spring wheat–pea and spring wheat–fallow. Each phase of the crop rotation was present in every year. From 1984 to 2004, the continuous spring wheat completed 21 cycles and 2-yr rotations completed >10 cycles. In STCW, plots were tilled with a sweep plow before spring wheat seeding to prepare a seedbed in the spring. In FSTCW and FSTW-B/P, plots were tilled with standard sweeps (0.45 m wide with medium crown) and rods in the fall, followed by tandem disk tillage in the spring to prepare the seedbed. Similarly, in STW-F, plots were tilled with a tandem disk before seeding in the spring. All tilled plots were cultivated to a depth of 10 cm. In NTCW, plots were left undisturbed, except in 1992 when the southern halves of the plots were subsoiled using paratillage to a depth of 30 cm (Pikul and Aase, 1999, 2003). The southern halves of plots of all other treatments were also paratilled in 1992 (Pikul and Aase, 1999, 2003). Pikul and Aase (1999, 2003) reported that continuous tillage from 1983 to 1992 had resulted in the development of a compact layer that impeded water movement and root growth at a depth of around 10 cm, for which they evaluated the effect of paratilling on soil and crop responses compared with no paratilling. Weeds in NTCW were controlled by applying preplant and postharvest herbicides and in other treatments by a combination of herbicides and sweep tillage to a depth of 10 cm as needed. Treatments were arranged in a randomized complete block with four replications. Individual plot size was 12 by 30 m.

Crop Management

At the time of land preparation or planting crops in April and May, N fertilizer was broadcast at 56 kg N ha^{-1} as NH_4NO_3 (34% N) from 1983 to 1985, 34 kg N ha^{-1} from 1986 to 1996 (Aase and Pikul, 1995; Pikul and Aase, 1999, 2003), and 70 kg N ha^{-1} as urea (46% N) and monoammonium phosphate (18% N, 46% P) from 1997 to 2004 for wheat in all plots except in STW-F, which received 34 kg N ha^{-1} from 1983 to 1996 and 70 kg N ha^{-1} from 1997 to 2004 during wheat years. For barley in FSTW-B/P, N fertilizer was broadcast at 56 kg N ha^{-1} as NH_4NO_3 from 1983 to 1985, 34 kg N ha^{-1} from 1986 to 1996 (Aase and Pikul, 1995; Pikul and Aase, 1999, 2003), and 70 kg N ha^{-1} as urea and monoammonium phosphate from 1997 to 1999. Similarly, for pea in FSTW-B/P from 2000 to 2004, N fertilizer was broadcast at 5 kg N ha^{-1} when monoammonium phosphate was applied as P fertilizer. The target available N (N available for plant uptake) for spring wheat and barley from 1983 to 1996 were not known but N rates specified above were thought to be adequate to produce optimum crop yields under dryland conditions (Aase and Pikul, 1995; Pikul and Aase, 1999, 2003). From 1997 to 2004, however, N rates to crops were applied as recommended by Montana State University with various yield goals and protein contents (spring wheat, 2350 kg ha^{-1} and 13%, respectively; barley, 2400 kg ha^{-1} and 12.5%; and pea, 1100 kg ha^{-1} and 20%) (Eastern Agricultural Research Center, 1997). Long-term P requirements (1983–1996) were made by incorporating a single application of P fertilizer at 560 kg P ha^{-1} as monoammonium phosphate to a depth of 5 cm to spring wheat, barley, and pea in all plots in 1983 (Aase and Pikul, 1995; Pikul and Aase, 1999, 2003). From 1997 to 2004, P fertilizer was applied annually at 56 kg P ha^{-1} in all treatments. Potassium fertilizer was not applied from 1983 to 1996 but was applied at 48 kg K ha^{-1} as muriate of potash (60% K) from 1997 to 2004 in all treatments.

Spring wheat (cv. Lew [unknown source] from 1983–1996 and McNeal [foundation seed, Montana State Univ.] from 1997–2004) was planted at 74 kg ha^{-1}, barley (cv. Hector [unknown source] from 1983–1996 and Certified Tradition [Busch Agricultural Resources, Fargo, ND] from 1997–1999) at 84 kg ha^{-1}, and pea (cv. Majoret [Macintosh Seed, Havre, MT] from 2000–2004) at 160 kg ha^{-1} in April of every year using a double disk opener with a row spacing of 20 to 25 cm from 1983 to 1996 and a Versatile no-till drill from 1997 to 2004. Growing season weeds were controlled with selective postemergence herbicides appropriate for each crop. Contact herbicides were applied at postharvest and preplanting and fallow plots were tilled with sweeps as needed to control weeds. From 1983 to 1993 and in 1995, crop grain and biomass yields were determined by cutting bundle samples from five 1-m-long rows from six areas in each plot in July and August each year (Aase and Pikul, 1995; Pikul and Aase, 1999). The bundle samples were dried, weighed, and threshed, from which grain and biomass (stems + leaves) yields were determined. In 1994 and from 1996 to 2004, grain yield was determined from a swath of 1.5-m width by 10 to 30 m long with a combine harvester in central rows. Biomass yield was measured by harvesting plants from an area of 0.5 by 1 m outside yield rows after separating grain from straw and oven drying a subsample at 60°C for 3 d.

Residue and Soil Sample Collection and Analysis

In October 2004, soil surface crop residue samples were collected from five 30- by 30-cm areas randomly in the central rows of the plot—two to three samples from paratilled areas and another two to three from nonparatilled areas, composited, washed with water to remove soil, and dried in the oven at 60°C to obtain dry-matter weight. Samples were ground to pass a 1-mm screen before C analysis. After removing the residue, 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 fractions. Two separate soil cores (5-cm i.d.), one from a paratilled and another from a nonparatilled area within a plot, were taken from 0 to 5 and 5 to 20 cm and composited within a depth to determine bulk density.

Total C concentration in the surface residue was determined by using a C and N analyzer (Model 661–900–800, LECO Corp., St Joseph, MI). Carbon content in the residue was determined by multiplying dry-matter weight by C concentration. The SOC and total C concentrations in soil samples were determined by using the C and N analyzer after grinding to <0.5 mm and pretreating the soil with or without 5% H_2SO_3 to remove inorganic C (Nelson and Sommers, 1996). The SIC was determined by deducting SOC from total C.

For determining POC, 10 g of soil was dispersed with 30 mL of 5 g L^{-1} sodium hexametaphosphate by shaking for 16 h and the solution was poured through a 0.053-mm sieve (Cambardella and Elliott, 1992). The solution and particles that passed through the sieve and contained mineral-associated and water-soluble C were dried at 50°C for 3 to 4 d and total C concentration was determined by using the analyzer as above. The POC concentration was determined by the difference between total C in the whole soil and that in the particles that passed through the sieve after correcting for the sand content. The PCM in air-dried soils was determined by the method modified by Haney et al. (2004). Ten grams of soil was moistened with water at 50% field capacity (0.25 m^3 m^{-3} [Aase and Pikul, 2000; Pikul and Aase, 2003]) and placed in a 1-L jar containing beakers with 2 mL of 0.5 mol L^{-1} NaOH to trap evolved CO_2 and 20 mL of water to maintain high humidity. Soils were incubated in the jar at 21°C for 10 d. At 10 d, the beaker containing NaOH was removed from the jar and PCM concentration was determined by measuring CO_2 absorbed in NaOH, which was back-titrated with 1.5 mol L^{-1} $BaCl_2$ and 0.1 mol L^{-1} HCl. The moist soil used for determining PCM was subsequently used for determining MBC by the modified fumigation–incubation method for air-dried soils (Franzluebbers et al., 1996). The moist soil was fumigated with ethanol-free chloroform for 24 h and placed in a 1-L jar containing beakers with 2 mL of 0.5 mol L^{-1} NaOH and 20 mL of water. As with PCM, fumigated moist soil was incubated for 10 d and CO_2 absorbed in NaOH was back-titrated with $BaCl_2$ and HCl. The MBC concentration was calculated by dividing the amount of CO_2–C absorbed in NaOH by a factor of 0.41 (Voroney and Paul, 1984) without subtracting the values from the unfumigated control (Franzluebbers et al., 1996).

The contents of SOC, SIC, POC, PCM, and MBC at 0- to 5- and 5- to 20-cm depths were calculated by multiplying their concentrations by the bulk density and thickness of the soil layer. Since bulk density at the time of measurement was not significantly influenced by treatments, bulk density values of 1.28 and 1.51 Mg m^{-3} at 0 to 5 and 5 to 20 cm, respectively, were used to convert concentrations of soil C fractions into contents. The total contents at 0 to 20 cm were determined by summing the contents at 0 to 5 and 5 to 20 cm.

Data Analysis

Data for crop biomass returned to the soil in each year from 1984 to 2004 and mean annualized biomass as influenced by treatments were analyzed using the MIXED procedure of SAS, with year considered a repeated measure factor (Littell et al., 1996). Treatment was considered as the fixed effect and replication as the random effect. Similarly, data for soil surface residue amount and C content and SOC, SIC, POC, PCM, and MBC contents in 2004 were analyzed using the MIXED procedure, with treatment as the fixed effect and replication as the random effect. Since each phase of each crop rotation was present in every year, data for phases were averaged within a rotation and the averaged value was used for a crop rotation for the analysis. Since crop biomass was absent during the fallow phase of the rotation, biomass of spring wheat during the crop year in the STW-F rotation was divided by 2 to calculate the annualized yield. Means were separated by using the least square means test when treatments were significant. Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

RESULTS AND DISCUSSION

Crop Biomass Yield

For measuring the effect of total crop residue returned to the soil from 1984 to 2004 on soil C fractions, data for crop biomass (stems + leaves) or straw yield for NTCW, FSTCW, and STW-F from 1984 to 1993 were taken from Aase and Pikul (1995) while those for these treatments from 1994 to 2004 and for STCW and FSTW-B/P from 1984 to 2004 were measured from the experiment (Fig. 1). Crop biomass yield varied significantly between treatments and years. Biomass was normally lower in STW-F than in other treatments in all years, except in 1984 and 1995 when differences between treatments were not significant. Compared with NTCW, biomass was lower in FSTCW and FSTW-B/P in 1985, 1990, and 1996 and lower in STCW in 1996 and 1999. Similarly, compared with FSTW-B/P, biomass was lower in STCW and NTCW in 1999 and lower in FSTCW in 2001 but was higher in NTCW and STCW in 2000 and 2002.

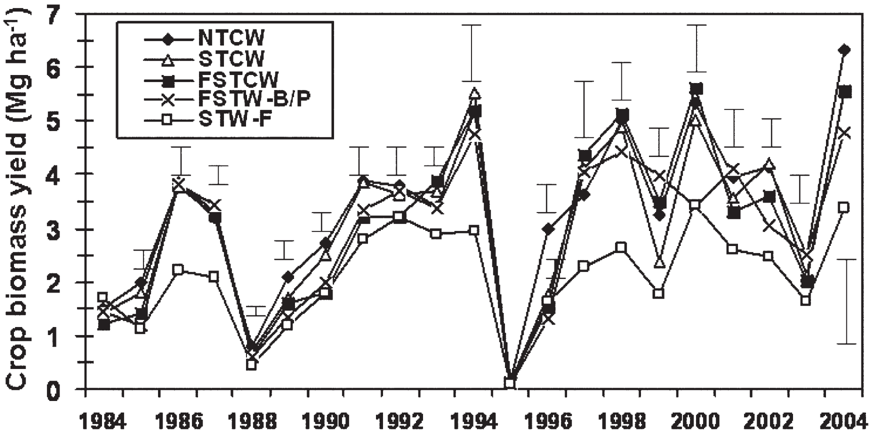

Fig. 1. Effects of tillage and cropping sequence on crop biomass (stems + leaves) residue returned to soil from 1984 to 2004 at the experimental site, 11 km north of Culbertson, MT. FSTCW represents fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-till continuous spring wheat; STCW, spring-tilled continuous spring wheat; and STW-F, spring-tilled spring wheat–fallow. Bars above or below biomass yield in a year represent LSD at *P* = 0.05. For measuring the effect of total crop residue returned to the soil from 1984 to 2004 on soil C fractions, data for crop biomass or straw yield for treatments NTCW, FSTCW, and STW-F from 1984 to 1993 were taken from Aase and Pikul (1995).

The lower biomass in STW-F than in other treatments was due to the absence of a crop during the fallow phase of the rotation; however, similar biomass between STW-F and most other treatments in five out of 21 yr suggests that fallowing produced biomass of the successive crops twice as high as that produced by other treatments during these years, probably by conserving soil water during fallow. Studies have shown that fallowing can conserve soil water due to reduced transpiration of plants and increase grain yield and biomass of succeeding crops (Aase and Pikul, 1995; Pikul et al., 1997; Farhani et al., 1998; Lenssen et al., 2007). Similarly, higher biomass in NTCW than in certain treatments in some years was probably due to increased soil water storage, because no-till can increase soil water storage compared with conventional tillage (Deibert et al., 1986; Farhani et al., 1998; Lenssen et al., 2007). In contrast, higher biomass in FSTW-B/P than in some treatments and years was possibly due to a rotation effect because of reduced incidences of diseases, pests, and weeds.

Variations in the amount and distribution of total monthly precipitation during the growing season (April–August) probably resulted in differences in crop biomass among years. The higher biomass in all treatments, except in STW-F, in 1986, 1991, 1994, 1998, 2000, and 2004 than in other years was probably a result of above-average precipitation and its uniform distribution during the growing season. Total growing season precipitation was 61 mm higher in 1986, 63 mm higher in 1991, 8 mm higher in 1994, 101 mm higher in 2000, and 30 mm higher in 2004 than the 105-yr average (Table 1). The monthly total precipitation during the growing season was also much more uniformly distributed in these years than in others. In contrast, lower biomass in 1988, regardless of treatments, was probably due to below-aver-

Table 1. Monthly total precipitation from 1984 to 2004 near the study site 11 km north of Culbertson, MT.

Year	April	May	June	July	August	Total Apr.–Aug.	Total annual
				mm			
1984	8	21	52	6	9	96	198
1985	33	59	17	33	27	169	317
1986	18	80	64	93	100	354	449
1987	14	102	29	100	20	264	356
1988	16	25	45	18	11	114	236
1989	59	45	31	74	34	243	368
1990	16	55	63	54	40	228	282
1991	68	67	113	41	15	303	412
1992	73	30	103	48	65	318	401
1993	5	26	60	131	75	296	377
1994	16	54	114	54	12	249	302
1995	22	27	35	68	61	213	312
1996	11	39	49	88	0	187	346
1997	23	17	22	117	45	224	282
1998	8	27	77	82	23	217	395
1999	6	79	28	77	24	213	281
2000	20	28	120	163	10	341	488
2001	39	9	91	206	4	348	378
2002	13	32	85	46	38	214	291
2003	17	69	114	114	42	356	409
2004	20	73	30	84	64	270	378
105-yr avg.†	31	53	75	52	36	240	340

† The 105-yr average precipitation data were taken from Culbertson, MT, which is 11 km south of the study site.

Table 2. Effects of tillage and cropping sequence on mean crop biomass (stems + leaves) yield (averaged across crop rotation phases and years) returned to the soil from 1984 to 2004 and soil surface residue amount and C content in 2004 at the study site 11 km north of Culbertson, MT.

Tillage and cropping sequence†	Mean crop biomass	Soil surface residue amount	Soil surface residue C content
	Mg ha^{-1}		
NTCW	3.91 a‡	3.07 a	1.27 a
STCW	3.59 a	2.70 ab	1.17 ab
FSTCW	3.63 a	3.29 a	1.39 a
FSTW-B/P	3.58 a	2.84 ab	1.13 ab
STW-F	2.31 b	2.08 b	0.87 b
P value	<0.001	0.043	0.040

† FSTCW, fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-till continuous spring wheat; STCW, spring-tilled continuous spring wheat; STW-F, spring-tilled spring wheat–fallow.

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

age precipitation. A hail storm during the growing season destroyed plants in 1995, thereby causing lower biomass that year.

Mean annualized biomass (averaged across rotation phases and years) of spring wheat, barley, and pea from 1984 to 2004 was significantly higher in NTCW, STCW, FSTCW, and FSTW-B/P than in STW-F (Table 2), suggesting that fallowing reduced the amount of biomass residue returned to the soil. For determining changes in crop and soil responses due to improved management practices compared with the conventional practice (STW-F), data for crop biomass, surface residue, and soil C fractions for STW-F were deducted from other treatments and are shown in Table 3. Mean crop biomass was 53 to 66% greater in other treatments than in STW-F (Table 3). Similar results of lower crop biomass residue returned to the soil with crop–fallow than with continuous cropping, regardless of tillage, in drylands of the northern and central Great Plains have been reported by various researchers (Aase and Pikul, 1995; Halvorson et al., 2002a, 2002b; Sherrod et al., 2003; Sainju et al., 2006a). Tillage, however, did not influence crop biomass in the continuous spring wheat system. Several researchers also found that tillage has less influence than cropping intensity on crop biomass in the northern Great Plains (Halvorson et al., 2002b; Sainju et al., 2006a, 2006b).

Soil Surface Crop Residue Amount and Carbon Content

After 21 yr of tillage and cropping sequence, soil surface residue amount and C content in 2004 were significantly influenced by treatments (Table 2). Residue amount and C content were 46 to 60% higher in NTCW and FSTCW than in STW-F (Tables 2 and 3). Although residue amount and C content increased by 30 to 34% in STCW and FSTW-B/P compared with STW-F, differences were not significant. Similar to crop biomass, tillage did not influence residue amount and C content in the continuous spring wheat system.

The lower surface residue amount and C content in STW-F than in other treatments was due to a reduced amount of crop biomass returned to the soil (Table 2). The fallow period is a time of high microbial activity and decomposition of organic matter with no input of crop residue (Halvorson et al., 2002b). As a result, rapid decomposition of residue, followed by reduced input during fallow, could have reduced the amount of surface residue and C content in STW-F. A nonsignificant difference among tillage treatments in continuous spring wheat suggests, however, that tillage did not alter the rate of decomposition of spring wheat residue in the soil. The harsh environmental conditions and cold weather of the northern Great Plains could have limited the decomposition of crop residues, regardless of tillage. Sainju et al. (2006a, 2006b) also did not observe a significant influence of 6 yr of tillage on dryland soil surface residue amount and C content in the northern Great Plains. Another possible reason for the nonsignificant effect of tillage on surface residue could be due to paratilling of the southern halves of all treatments in 1992 (Pikul and Aase, 1999, 2003). Since residue samples were a mixture from both paratilled and nonparatilled areas of the plot, it could be possible that paratilling increased decomposition of residue compared with nonparatilling, thereby resulting in similar residue levels between tilled and no-till treatments in the continuous spring wheat system. Similarly, inclusion of legumes, such as pea, in rotation with spring wheat also did not influence the residue amount and C content (Table 2). Considering that the amount of residue lost or gained due to the actions of wind and water is negligible, the amount of residue left in the soil after 21 yr varied

Table 3. Increases in mean crop biomass (stems + leaves) yield (averaged across crop rotation phases and years), soil surface residue amount and C content, and soil C fractions at the 0- to 20-cm depth in other treatments (shown below) compared with a spring-tilled spring wheat–fallow (STW-F) system after 21 yr of tillage and cropping sequence at the study site 11 km north of Culbertson, MT.

Tillage and cropping sequence†	Mean annualized crop biomass	Soil surface residue		Soil C fractions‡			
		Amount	C content	SIC	SOC	POC	PCM
	Mg ha^{-1}			Mg C ha^{-1}			kg CO_2–C ha^{-1}
NTCW	2.37 (66)§	0.99 (48)	0.40 (46)	2.88 (88)	8.4 (39)	3.86 (141)	134 (35)
STCW	1.89 (53)	0.62 (30)	0.30 (34)	2.42 (74)	8.4 (39)	2.84 (104)	186 (49)
FSTCW	1.92 (53)	1.21 (58)	0.52 (60)	1.96 (60)	6.7 (31)	2.82 (103)	87 (23)
FSTW-B/P	2.07 (58)	0.76 (34)	0.26 (30)	1.57 (48)	5.4 (25)	1.16 (42)	110 (29)

† FSTCW, fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-till continuous spring wheat; STCW, spring-tilled continuous spring wheat.

‡ SIC, soil inorganic C; SOC, soil organic C; PCM, potential C mineralization; POC, particulate organic C.

§ Number in parentheses represents percentage increase compared with STW-F.

Table 4. Effects of tillage and cropping sequence on soil inorganic C (SIC), soil organic C (SOC), and soil total C (STC) contents at the 0- to 20-cm depth in 2004 at the study site 11 km north of Culbertson, MT.

Tillage and cropping sequence†	SIC at soil depth			SOC at soil depth			SIC/STC ratio at soil depth		
	0–5 cm	5–20 cm	0–20 cm	0–5 cm	5–20 cm	0–20 cm	0–5 cm	5–20 cm	0–20 cm
	Mg C ha^{-1}						g kg^{-1} STC		
NTCW	3.15 a‡	2.98 a	6.13 a	9.8 a	20.2 a	30.0 a	243 a	128 a	169 a
STCW	2.73 ab	2.94 a	5.67 a	9.5 a	20.5 a	30.0 a	221 ab	125 a	158 a
FSTCW	1.87 bc	3.34 a	5.21 a	9.2 ab	19.1 a	28.3 a	167 bc	144 a	153 a
FSTW-B/P	2.11 b	2.71 a	4.82 ab	8.0 b	19.0 a	27.0 a	216 ab	122 a	151 a
STW-F	1.03 c	2.22 a	3.25 b	5.9 c	15.7 b	21.6 b	144 c	123 a	131 a
P **value**	0.002	NS§	0.045	<0.001	0.043	0.002	0.046	NS	NS

† FSTCW, fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-till continuous spring wheat; STCW, spring-tilled continuous spring wheat; STW-F, spring-tilled spring wheat–fallow.

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

§ Not significant.

from 3.6% of total crop biomass returned to the soil in STCW to 4.3% in FSTCW and STW-F. Because of the higher residue amount and C content under continuous cropping than under crop–fallow, regardless of tillage (Table 2), continuous cropping can reduce the potential for soil erosion and conserve C in residue better than crop–fallow. Soil surface residue amount is directly related to residue cover (Sainju et al., 2006a), which in turn can reduce the potential for soil erosion (Fenster et al., 1977; Fryrear, 1985). Since 2 Mg ha^{-1} surface residue is needed to effectively control soil erosion (Fenster et al., 1977; Fryrear, 1985), all treatments can reduce erosion (Table 2) but continuous cropping may be even more effective than crop–fallow for controlling erosion.

Soil Inorganic Carbon

The SIC at 0 to 5 and 0 to 20 cm was significantly influenced by treatments (Table 4). At 0 to 5 cm, SIC was greater in NTCW than in FSTCW, FSTW-B/P, or STW-F, and greater in STCW and FSTW-B/P than in STW-F. At 0 to 20 cm, SIC was greater in NTCW, STCW, and FSTCW than in STW-F. Compared with STW-F, increases in SIC at 0 to 20 cm in other treatments ranged from 48 to 88% (Table 3). An orthogonal contrast of no-till vs. spring tillage plus fall and spring tillage in continuous spring wheat (data not shown) indicated that SIC was significantly ($P \leq 0.05$) greater in no-till than in tillage treatments at 0 to 5 cm.

A reduction in tillage frequency and an increase in cropping intensity increased SIC, since SIC at 0 to 20 cm decreased continuously in the order from NTCW to STW-F (Table 4). This order is somewhat similar to the mean annualized amount of crop biomass returned to the soil (Table 2). It is not clear why a reduction in tillage frequency and an increase in cropping intensity increased SIC but a possible explanation could be that increased biomass residue accumulated at the soil surface increased SIC in NTCW compared with other treatments due to increased Ca and Mg inputs from the residue. Increased biological activities from plants and soil microbes due to increased cropping intensity can increase the formation of $CaCO_3$, thereby increasing SIC (Cerling, 1984; Monger, 2002). Increased SIC in other treatments also could have resulted from increased addition of soil amendments, such as fertilizers containing Ca, that could lead to the increased formation of $CaCO_3$ in the annual cropping system compared with STW-F, where fertilizers were applied to crops only in alternate years (Amundson and Lund, 1987; Mikhailova and Post, 2006). The greater SIC at 0 to 5 cm in NTCW than in FSTCW, FSTW-B/P, or STW-F (Table 4) could be due to placement of fertilizers at the soil surface. Aase and Pikul (1995) reported that yearly application of NH_4NO_3 decreased soil pH by 0.6 yr^{-1} from 1983 to 1993, regardless of treatment. Soil pH measured in 2004 was not influenced by treatments and averaged 4.98 at 0 to 5 cm and 5.95 at 5 to 20 cm, so lower SIC in STW-F than in other treatments could not have resulted from differences in soil pH between treatments. Another possible reason for lower SIC in STW-F could be due to greater dissolution of SIC as a result of higher soil water content in the fallow years, since fallowing increases soil water content and temperature (Eck and Jones, 1992; Aase and Pikul, 1995; Jones and Popham, 1997; Pikul et al., 1997). Our findings of increased SIC at 0 to 5 cm in NTCW compared with FSTCW (Table 4) are in contrast to those obtained by Cihacek and Ulmer (2002), who have reported increased SIC at the surface soil with cultivation in the northern Great Plains. Increased SIC content with alternative management practices is also a measure of increased C sequestration in the soil, since SIC content at 0 to 20 cm contributed from 13 to 17% of total soil C (organic C + inorganic C) (Table 4).

The proportion of total soil C in SIC, i.e., SIC/total soil C ratio, at 0 to 5 cm was higher in NTCW than in FSTCW or STW-F and higher in STCW and FSTW-B/P than in STW-F (Table 4). This indicates that reduced tillage frequency and increased cropping intensity also increased the proportion of SIC relative to total soil C. Such increases in the reduced tillage system were particularly observed at the surface soil layer, where crop residues accumulate due to reduced soil disturbance.

Soil Organic Carbon

Differences in the amount of crop biomass residue returned to the soil due to cropping sequences and tillage resulted in a significant difference in SOC between treatments in 2004 (Table 4). The SOC at 0 to 5 cm was higher in NTCW and STCW than in FSTW-B/P or STW-F and higher in FSTCW and FSTW-B/P than in STW-F. At 5 to 20 and 0 to 20 cm, SOC was higher in NTCW, STCW, FSTCW, and FSTW-B/P than in STW-F. Compared with STW-F, SOC at 0 to 20 cm in other treatments increased from 25 to 39% (Table 3). Although the concentration of SOC was higher at 0 to 5 than at 5 to 20 cm, the increased thickness of the soil layer and bulk density increased SOC content at 5 to 20 cm compared with 0 to 5 cm.

Assuming that reduced aboveground crop biomass also reduced belowground (root) biomass, the decreased SOC in STW-F compared with other treatments (Tables 3 and 4) was probably due to lower C inputs from both above- and belowground biomass. The mean annualized amount of aboveground crop residue returned to the soil was 53 to 66% lower in STW-F than in other treatments (Table 3). The reduced amount of crop residue, followed by its increased decomposition due to tillage and fallow (Halvorson et al., 2002b), could have reduced SOC in STW-F. This is consistent with the findings reported by several researchers in the northern and central Great Plains (Aase and Pikul, 1995; Peterson et al., 1998; Halvorson et al., 2002a, 2002b; Sainju et al., 2006a, 2006b). In contrast, greater SOC at 0 to 5 cm in NTCW and STCW than in FSTW-B/P probably resulted from decreased tillage frequency, followed by a change in the cropping system from continuous spring wheat to a spring wheat–barley/pea rotation. Decreased soil disturbance due to reduced tillage frequency could have reduced the mineralization rate of SOC, thereby increasing its level in NTCW and STCW, especially in the surface soil. Franzluebbers et al. (1999) reported that SOC level increased with reduced tillage frequency. Halvorson et al. (2002b) also reported increased SOC with reduced tillage intensity in the northern Great Plains. Tillage frequency, however, did not affect SOC in the continuous spring wheat system, probably because paratilling conducted in 1992 (Pikul and Aase, 1999, 2003) still had an influence on SOC in NTCW, STCW, and FSTCW in 2004. Pikul and Aase (1999, 2003) reported that paratilling reduced soil bulk density and compaction but increased soil water content and infiltration capacity compared with nonparatilling and the effects were still persistent after 2.5 yr. Increased SOC with continuous spring wheat compared with spring wheat–barley/pea could also be related to residue quality, such as C/N ratio, that results in different decomposition rates of residues in the soil. Residues of nonlegumes, such as spring wheat, with a higher C/N ratio decompose more slowly than those of legumes, such as pea, thereby resulting in higher SOC levels (Kuo et al., 1997; Sainju et al., 2003).

Because of the effect of paratilling and changes in depths of the soil sample collected at the beginning (0–8 cm in 1983) and end (0–5 and 5–20 cm in 2004) of the experiment, it is difficult to estimate the long-term effects of tillage and cropping sequence on soil C sequestration rates. Pikul and Aase (1995) reported that both soil bulk density and SOC concentration changed rapidly with depth. Considering that bulk density and SOC concentration measured at the 0- to 5-cm depth are similar to that at 0 to 8 cm, SOC content at 0 to 8 cm based on the values at 0 to 5 cm (Table 4) would be roughly equal to 15.7, 15.2, 14.7, 12.8, and 9.4 Mg C ha^{-1} in NTCW, STCW, FSTCW, FSTW-B/P, and STW-F, respectively, in 2004. Since the original level of SOC in 1983 was 16.8 Mg C ha^{-1}, the rough estimates of C sequestration rates would be −52, −76, −100, −190, and −352 kg C ha^{-1} yr^{-1} in NTCW, STCW, FSTCW, FSTW-B/P, and STW-F, respectively. It is not known if C loss in all treatments was due to the effect of paratilling conducted in 1992 (Pikul and Aase, 1999, 2003). Aase and Pikul (1995) reported that SOC levels in this experiment decreased from 1983 to 1993 in all treatments, with negligible decline in the annual crop treatment and a loss of 480 kg C ha^{-1} yr^{-1} in the crop–fallow treatment. It is also not known if soil samples collected in 1983 were treated with acid before SOC was determined by the C and N analyzer (Aase and Pikul, 1995). If total soil C (SIC + SOC) was used for determining C sequestration rates for different treatments, total soil C content at 0 to 8 cm based on the value at 0 to 5 cm (Table 4) (as assumed above) would be roughly equal to 20.7, 19.6, 17.7, 16.2, and 11.1 Mg C ha^{-1} in NTCW, STCW, FSTCW, FSTW-B/P, and STW-F, respectively, in 2004. If the original C level in 1983 was assumed to be 16.8 Mg C ha^{-1}, the approximate C sequestration rates would be 186, 133, 43, −29, and −271 kg C ha^{-1} yr^{-1} in NTCW, STCW, FSTCW, FSTW-B/P, and STW-F, respectively. For an accurate estimation of C sequestration rates in these treatments, however, soil samples should be collected at the 0- to 8-cm depth, as done at the beginning of the experiment in 1983, only from the nonparatilled portion of the treatment and total soil C (SIC + SOC) concentration and bulk density determined.

Particulate Organic Carbon

Similar to SOC, differences in the amount of crop residue returned to the soil among treatments significantly affected POC in 2004 (Table 5). The POC at 0 to 5 and 0 to 20 cm was higher in NTCW than in FSTW-B/P or STW-F and higher in STCW and FSTCW than in STW-F. At 5 to 20 cm, POC was higher in NTCW than in FSTW-B/P or STW-F and higher in STCW than in STW-F. Compared with STW-F, POC at 0 to 20 cm in other treatments increased from 42 to 141% (Table 3).

Greater POC in NTCW than in other treatments (Table 5) suggests that reduced tillage frequency and increased cropping intensity increased POC, similar to SOC. In contrast, lower POC in FSTW-B/P than in NTCW indicates that increased tillage frequency, fol-

Table 5. Effects of tillage and cropping sequence on soil particulate organic C (POC) contents and potential C mineralization (PCM) at the 0- to 20-cm depth in 2004 at the study site 11 km north of Culbertson, MT.

Tillage and cropping sequence†	POC at soil depth			PCM at soil depth		
	0–5 cm	5–20 cm	0–20 cm	0–5 cm	5–20 cm	0–20 cm
	Mg C ha^{-1}			kg CO_2–C ha^{-1}		
NTCW	3.45 a‡	3.14 a	6.59 a	207 a	306 abc	513 ab
STCW	2.91 ab	2.66 ab	5.57 ab	194 a	361 a	565 a
FSTCW	3.15 ab	2.40 abc	5.55 ab	184 ab	282 bc	466 b
FSTW-B/P	1.88 bc	2.01 bc	3.89 bc	145 bc	344 ab	489 ab
STW-F	1.00 c	1.73 c	2.73 c	117 c	262 c	379 c
P value	0.025	0.042	0.020	0.003	0.042	0.007

† FSTCW, fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-till continuous spring wheat; STCW, spring-tilled continuous spring wheat; and STW-F, spring-tilled spring wheat–fallow.

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

Table 6. Effects of tillage and cropping sequence on soil microbial biomass C (MBC)/soil organic C (SOC) and potential C mineralization (PCM)/MBC ratios at the 0- to 20-cm depth in 2004 at the study site 11 km north of Culberson, MT.

Tillage and cropping sequence†	MBC/SOC at soil depth			PCM/MBC at soil depth		
	0–5 cm	5–20 cm	0–20 cm	0–5 cm	5–20 cm	0–20 cm
	——— g kg^{-1} SOC ———			——— g kg^{-1} MBC ———		
NTCW	49 b‡	62 a	57 b	446 ab	243 a	299 a
STCW	49 b	64 a	59 b	426 b	288 a	322 a
FSTCW	41 b	62 a	55 b	482 a	240 a	298 a
FSTW-B/P	47 b	64 a	59 b	389 c	286 a	310 a
STW-F	63 a	79 a	75 a	317 d	224 a	244 a
P value	0.008	NS§	0.044	<0.001	NS	NS

† FSTCW, fall- and spring-tilled continuous spring wheat; FSTW-B/P, fall- and spring-tilled spring wheat–barley (1984–1999) followed by spring wheat–pea (2000–2004); NTCW, no-till continuous spring wheat; STCW, spring-tilled continuous spring wheat; and STW-F, spring-tilled spring wheat–fallow.

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

§ Not significant.

lowed by a change in the cropping sequence from continuous spring wheat to a spring wheat–barley/pea rotation decreased the labile pool of SOC. Since the mean annualized amount of crop residue returned to the soil in FSTW-B/P and NTCW were similar (Table 2), reduced POC in FSTW-B/P could be a result of increased mineralization of crop residue and soil organic matter due to increased tillage frequency, followed by a difference in residue quality (C/N ratio) of the two cropping systems. Similarly, lower POC in STW-F than in other treatments suggests that the reduced amount of crop residue returned to the soil and its rapid mineralization due to fallow (Table 2) probably reduced POC, provided that the amount of belowground biomass, similar to aboveground biomass, is also lower in STW-F than in other treatments.

An orthogonal contrast of no-till vs. spring tillage plus fall and spring tillage in the continuous wheat system (data not shown) indicated that POC was significantly higher in no-till than in tilled treatments at 5 to 20 and 0 to 20 cm but not at 0 to 5 cm. This suggests that reduced tillage increased POC more in the subsurface than in the surface soil. This trend was in contrast to SOC, which increased with reduced tillage mainly at the surface soil (Table 4). Tillage may result in more rapid mineralization of coarse fragments of soil organic matter in the subsurface than in the surface soil, since POC contains mostly coarse fractions of soil organic matter (Cambardella and Elliott, 1992). The proportion of SOC in POC was not influenced by treatments and averaged 280, 126, and 175 g kg^{-1} SOC at 0 to 5, 5 to 20, and 0 to 20 cm, respectively. Comparison of the effect of treatments on SOC and POC (Tables 4 and 5) revealed, however, that POC is more sensitive to changes due to tillage and cropping system than SOC. At 0 to 20 cm, SOC content in STW-F was two-third while POC content was one-third of that in NTCW (Tables 4 and 5).

Potential Carbon Mineralization and Microbial Biomass Carbon

Differences in tillage frequency and cropping sequences between treatments also significantly influenced PCM (Table 5). The PCM at 0 to 5 cm was higher in NTCW and STCW than in FSTW-B/P or STW-F and higher in FSTCW than in STW-F. At 5 to 20 cm, PCM was higher in STCW than in FSTCW or STW-F and higher in FSTW-B/P than in STW-F. Similarly, at 0 to 20 cm, PCM was higher in STCW than in FSTCW or STW-F and higher in NTCW, FSTCW, and FSTW-B/P than in STW-F. Compared with STW-F, PCM at 0 to 20 cm in other treatments increased from 23 to 49% (Table 3). The MBC was not influenced by treatments and averaged 412, 1232, and 1644 kg CO_2–C ha^{-1} at 0 to 5, 5 to 20, and 0 to 20 cm, respectively.

The greater PCM at 0 to 5 cm in NTCW and STCW than in FSTW-B/P (Table 5) was probably a result of decreased tillage frequency, followed by differences in residue quality (C/N ratio) of crops between continuous spring wheat and the spring wheat–barley/pea rotation that resulted in reduced mineralization of SOC and crop residue of higher C/N ratio at the surface, similar to that observed for SOC and POC. Similarly, greater PCM at 5 to 20 and 0 to 20 cm in STCW than in FSTCW was probably due to decreased tillage frequency in the continuous spring wheat system. A significant increase in PCM at 0 to 5 cm in no-till vs. spring tillage plus fall and spring tillage in continuous spring wheat as observed by orthogonal contrast (data not shown) also indicates that reduced tillage increased PCM in the surface soil. In contrast, lower PCM in STW-F than in other treatments (Tables 3 and 5) was probably a result of the reduced amount of crop residue returned to the soil (Table 2). Since PCM measures microbial activities in the soil (Franzluebbers et al., 1995), increased PCM levels in NTCW and STCW suggests that reduced tillage with increased cropping intensity of nonlegume crops increased soil biological quality by increasing microbial activities (Saffigna et al., 1989; Bremner and Van Kessel, 1992).

The proportion of SOC in PCM was not influenced by treatments and averaged 20.0, 16.6, and 17.7 g kg^{-1} SOC at 0 to 5, 5 to 20, and 0 to 20 cm, respectively. These values were below or within the range of reported values of 20.0 to 29.9 g kg^{-1} SOC (Franzluebbers et al., 1995; Sainju et al., 2003). In contrast, the proportion of SOC as MBC, i.e., the MBC/SOC ratio, was influenced by treatments and was greater in STW-F than in other treatments (Table 6). It could be possible that microbial biomass was higher during the fallow period, thereby increasing MBC relative to SOC in STW-F. Fallowing increases soil water storage and temperature (Eck and Jones, 1992; Jones and Popham, 1997), which can increase microbial biomass and activities, resulting in increased mineralization of SOC (Haas et al., 1974, p. 2–35; Halvorson et al., 2002a, 2002b). The PCM/MBC ratio, i.e., the proportion of CO_2 respired by microorganisms, at 0 to 5 cm was higher in FSTCW than in STCW, FSTW-B/P, or STW-F, and higher in NTCW and STCW than in FSTW-B/P or STW-F (Table 6). This suggests that tillage and fallowing stimulated microbial biomass and activities relative to soil organic matter at the surface soil, probably a result of residue incorporation into the soil due to tillage and increased soil water content and temperature due to fallow. The lower MBC/SOC ratio at 0 to 5 than at 5 to 20 cm (Table 6) was due to lower MBC at 0 to 5 cm (412 kg CO_2–C ha^{-1}) than at 5 to 20 cm (1232 kg CO_2–C ha^{-1}) relative to SOC. In contrast, a higher PCM/MBC ratio at 0 to 5 than at 5 to 20 cm was due to similar or slightly higher PCM at 0 to 5 than at 5 to 20 cm (Table 5) but lower MBC at 0 to 5 than at 5 to 20 cm. This indicates that PCM changes more rapidly due to tillage and crop management practices than MBC at the soil surface. Higher PCM/MBC ratios at 0 to 5 than at 5 to 20 cm in the dryland soils of the northern Great Plains were also reported by Sainju et al. (2007).

CONCLUSIONS

Twenty-one years of tillage and dryland cropping sequences in the northern Great Plains significantly influenced the amount of crop biomass returned to the soil, the surface residue amount and C content, and soil C fractions. Crop biomass varied among treatments and years and the mean annualized biomass was lower in STW-F than in other treatments. As a result, surface residue C and soil C fractions were also lower in STW-F than in other treatments. When tillage frequency was increased and the cropping system changed, SIC, SOC, POC, and PCM at 0 to 5 cm were lower in FSTW-B/P than in NTCW. In the continuous spring wheat system, however, SIC and PCM at 0 to 5 cm and POC at 5 to 20 and 0 to 20 cm were higher in no-till than in tillage treatments but tillage did not influence SOC, possibly a result of paratilling conducted in 1992. Reduced tillage with continuous nonlegume cropping increased dryland C storage by reducing C loss due to mineralization, and improved soil quality by increasing microbial biomass and activities compared with conventional tillage with a legume–nonlegume crop rotation or spring wheat–fallow systems. Compared with the original SOC level, C was lost in all treatments after 21 yr, but the loss was much lower in reduced tillage with continuous cropping than in the conventional tillage with a spring wheat–fallow system.

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