TILLAGE AND CROPPING SYSTEMS

Tillage System and Crop Rotation Effects on Dryland Crop Yields and Soil Carbon in the Central Great Plains

Ardell D. Halvorson,* Gary A. Peterson, and Curtis A. Reule

ABSTRACT

Winter wheat (*Triticum aestivum* L.)–fallow (WF) using conventional stubble mulch tillage (CT) is the predominant production practice in the central Great Plains and has resulted in high erosion potential and decreased soil organic C (SOC) contents. This study, conducted from 1990 through 1994 on a Weld silt loam (Aridic Argiustoll) near Akron, CO, evaluated the effect of WF tillage system with varying degrees of soil disturbance [no-till (NT), reduced till (RT), CT, and bare fallow (BF)] and crop rotation [WF, NT wheat–corn (*Zea mays* L.)–fallow (WCF), and NT continuous corn (CC)] on winter wheat and corn yields, aboveground residue additions to the soil at harvest, surface residue amounts at planting, and SOC. Neither tillage nor crop rotation affected winter wheat yields, which averaged 2930 kg ha^{-1}. Corn grain yields for the CC (NT) and WCF (NT) rotations averaged 1980 and 3520 kg ha^{-1}, respectively. The WCF (NT) rotation returned 8870 kg ha^{-1} residue to the soil in each 3-yr cycle, which is 2960 kg ha^{-1} on an annualized basis. Annualized residue return in WF averaged 2520 kg ha^{-1}, which was 15% less than WCF (NT). Annualized corn residue returned to the soil was 3190 kg ha^{-1} for the CC (NT) rotation. At wheat planting, surface crop residues varied with year, tillage, and rotation, averaging WCF (NT) (5120 kg ha^{-1}) $>$ WF (NT) (3380 kg ha^{-1}) $>$ WF (RT) (2140 kg ha^{-1}) $>$ WF (CT) (1420 kg ha^{-1}) $>$ WF (BF) (50 kg ha^{-1}). Soil erosion potential was lessened with WCF (NT), CC (NT), and WF (NT) systems because of the large amounts of residue cover. Levels of SOC in descending order in 1994 were CC (NT) $\geq$ WCF (NT) $\geq$ WF (NT) = WF (RT) = WF (CT) $>$ WF (BF). Although not statistically significant, the CC (NT) treatment appeared to be accumulating more SOC than any of the rotations that included a fallow period, even more rapidly than WCF (NT), which had a similar amount of annualized C addition. Reduced tillage and intensified cropping increased SOC and reduced soil erosion potential.

The WF production system using CT is the most widely used crop management practice in the central Great Plains. In this system, weed control during the fallow period is maintained using five to six tillage operations. Herbicidal weed control can replace tillage and has made it possible to develop RT and NT winter wheat production systems. Reduced-till and NT systems conserve more water early in the fallow period than CT systems and often have as much water stored by May of the fallow year as CT systems have saved 3 to 4 more months later (Farahani et al., 1998). This has made it feasible to crop more frequently than is possible in the CT crop–fallow system in the central Great Plains (Shanahan et al., 1988; Halvorson, 1990; Peterson et al., 1993; Halvorson and Reule, 1994; Farahani et al., 1998). Winter wheat yields in a WCF rotation, even with 3 to 4 mo less fallow time, are usually equal to those in WF and may be potentially greater than in the monoculture WF system, thus making the RT and NT systems more profitable (Halvorson et al., 1994b; Dhuyvetter et al., 1996).

Reducing tillage with herbicidal weed control and intensifying the cropping system also has the potential to increase SOC (Campbell and Zentner, 1997; Halvorson et al., 2002; Havlin et al., 1990; Havlin and Kissel, 1997; Rasmussen and Smiley, 1997; Peterson et al., 1998). Annual increases in residue production within a cropping system and/or decreased tillage frequencies maintain SOC levels or even increase them with time, depending on the quantity and types of residue input to the soil (Larson et al., 1972; Rasmussen et al., 1980; Rasmussen and Rohde, 1988; Havlin et al., 1990; Peterson et al., 1998). Lal et al. (1998a, 1998b) have pointed out that general adoption of best management practices by farmers on cropland may help reverse the atmospheric enrichment of CO_2 resulting from U.S. emissions outside of agriculture by sequestering C in soil. This may be more difficult to achieve in semiarid areas, where crop yields are lower and biomass returns to the soil smaller, than in subhumid climatic regions. Furthermore, converting to a NT system and cropping more intensively in the central Great Plains can contribute to an improved environment by decreasing wind erosion and decreasing the atmospheric dust load (Fryrear, 1985; Papendick and Saxton, 1997).

We have limited information in the semiarid climate of the central Great Plains regarding the long-term effects of crop management practices on crop residue production and its subsequent effects on SOC (Bowman and Halvorson, 1998; Halvorson et al., 1999; Peterson et al., 1998). Our objectives were to evaluate the effect of WF tillage systems, with varying degrees of soil disturbance, and crop rotation [WF vs. WCF (NT) vs. CC (NT)] on winter wheat and corn yields, aboveground residue additions to soil at harvest, surface residue amounts at planting, and SOC.

MATERIALS AND METHODS

The study was conducted on a Weld silt loam soil (fine, smectitic, mesic Aridic Argiustoll) at the Central Great Plains

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Abbreviations: BF, bare fallow; CC, continuous corn; CT, conventional till; NT, no-till; RT, reduced till; SOC, soil organic carbon; WCF, wheat–corn–fallow; WF, winter wheat–fallow.

Research Station, Akron, CO, from 1990 through 1994. In 1989, a series of CT, RT, and NT plots that had been in existence since 1975 (Smika, 1990) were retained or converted into the following cropping and tillage treatments: WF (NT), WF (RT), WF (CT), WF (BF), WCF (NT), and CC (NT) (Halvorson et al., 1997). The WF tillage treatments were as follows:

1. CT: sweep tillage with Haybuster[1] undercutter as needed for weed control during fallow period with rod weeder operation just before planting (five to six tillage operations with average depth of about 8 cm).
2. BF: sweep tillage following wheat harvest, moldboard plow (10 to15-cm deep) in spring, sweep tillage (two to three operations) as needed for weed control, and rod weeder operation just before planting, all at an average depth of about 8 cm.
3. RT: residual herbicide after harvest and then summer tillage (two to three operations) as needed with sweep plow (average depth of about 8 cm) beginning when herbicide became ineffective and continuing until planting.
4. NT: residual herbicide after harvest and then contact herbicides (two to three applications) as needed for weed control during fallow period until wheat planting.

The WCF and CC treatments were totally NT production systems with herbicidal weed control. The plot layout was a randomized complete block design with four replications (Halvorson et al., 1997). All phases of all rotations were present each year. Nitrogen, as NH_4NO_3, was broadcast on the soil surface with no incorporation (56 kg N ha^{-1}) just before planting each winter wheat crop. Anhydrous ammonia was applied at a rate of 84 kg N ha^{-1} after corn emergence or just before corn planting from 1990 through 1992, with NH_4NO_3 being broadcast-applied (84 kg N ha^{-1}) just before corn planting in 1993 and 1994. In 1989, a blanket application (56 kg P ha^{-1}) of triple superphosphate was broadcast-applied to all plots. In 1993, 11 kg P ha^{-1} was band-applied with the seed at wheat planting. Soil test values from adjacent studies indicate a high level of available K in this soil. Plot sizes ranged from 11 by 30 m to 7.3 by 30 m, depending on the phase. Precipitation data were collected at a weather station located adjacent to the experiment.

Winter wheat (cultivar TAM 107) was planted each year in late September at a seeding rate of about 2.2 million seeds ha^{-1} with a NT disk drill at a row spacing of 18 cm. The wheat was harvested in early to mid-July each year. Wheat yields are expressed on a 120 g kg^{-1} water content basis. Corn (Pioneer hybrid 3732) was planted in late April to early May with a John Deere maximerge row planter with a disk opener at a planting rate of about 37 000 seeds ha^{-1}. The corn was generally harvested in mid- to late October each year. Corn grain yields are expressed on a 155 g kg^{-1} water content basis.

No broadleaf weed control was needed in the growing wheat crop. For corn, atrazine (6-chloro-N^2–ethyl-N^4–isopropyl-1, 3,5-trazine-2,3-diamine) plus paraquat (1,1-dimethyl-4,4-bipyridinium ion) or atrazine plus glyphosate [isopropylamine salt of *N*-(phosphonomethyl) glycine] was applied preplant from 1991 through 1994. In 1990, Dual [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methozy-1-methylethyl) acetamide] and Bladex {2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino]-2-methylpropionitrile} were applied to the corn plots for weed control, but weed control was poor in 1990. This resulted in a heavy broadleaf and grassy weed infestation in the CC (NT) plots in 1991. Weed control (broadleaf and grasses) was not as good in the CC (NT) plots as in the WCF (NT) plots, which were nearly weed-free most years.

Crop residue production was estimated by obtaining a total biomass sample at grain harvest from no less than a 1-m^2 area in each plot and subtracting grain yield. All grain yields were determined by harvesting a minimum of a 1.5- by 28-m area from each plot with a plot combine. Organic C input was estimated by assuming that the wheat and corn residues contained 45% C.

Surface residue levels at planting of each crop were estimated by hand-collecting all surface residue within a randomly chosen 0.5-m^2 quadrat from all plots. These samples were screened to remove soil, oven-dried at 65°C, and weighed.

Soil samples, one 3-cm-diam. core per plot, were collected in 30-cm increments to a depth of 180 cm from each treatment before planting and after harvest of wheat and corn for gravimetric total soil water content and NO_3–N analysis. Soil crop water use was estimated by subtracting the harvest soil water content from the planting soil water content. Estimated total water use by each crop was assumed to be soil water use plus growing season precipitation. During the study, no visual signs of runoff of precipitation from the plots were observed; therefore, loss of growing season precipitation to runoff or drainage was assumed to be zero. Soil NO_3–N was determined by Cd reduction with an autoanalyzer (Lachat Instruments, 1989) on a 5:1 extract/soil ratio using a 0.01 *M* $CaSO_4$ extracting solution.

Soil samples, a composite of six random 2-cm-diam. cores per plot, were collected from all plots after wheat and corn harvest in 1994 to assess SOC in the 0- to 7.6- and 7.6- to 15.2-cm soil depths. Surface crop residue was brushed aside before taking the soil sample. Soil bulk density was determined in each plot for each sampling depth by collecting four random 3.2-cm-diam. cores per plot. The soil cores were composited, oven-dried, weighed, and soil bulk density was calculated. Soil organic C was determined by dry combustion (Nelson and Sommers, 1996) using a Leco CHN-1000 autoanalyzer (Leco Corp., St. Joseph, MI). No free lime was present in any sample. Mass of SOC in the surface soil was calculated using the soil bulk density values from individual plots. Soil organic C concentration was measured in 1989 in each of the experimental plots for the 0- to 5-, 5- to 10-, and 10- to 20-cm soil depths; however, soil bulk densities were not measured.

Analyses of variance were performed using Analytical Software Statistix7 program (Analytical Software, 2000). When the analysis of variance was significant, an $LSD_{0.05}$ was used to determine differences between treatment means. All differences discussed are significant at the $P = 0.05$ probability level unless otherwise stated.

RESULTS AND DISCUSSION

Precipitation data in Table 1 show that our study was conducted under typical precipitation conditions and illustrate the high degree of variability that occurs in the Great Plains. Annual precipitation was above average in 1990 and 1993, below average in 1991 and 1994, and near average in 1992. The 87-yr average annual precipitation at the long-term weather station, adjacent to the study site, was 41.9 cm. Growing season precipitation for winter wheat (1 April to harvest) was 16.6, 21.2, 15.2, 14.5, and 8.9 cm for 1990, 1991, 1992, 1993, and 1994, respectively. Growing season precipitation for corn (1 May to harvest) was 41.3, 19.1, 31.0, 34.0, and 13.8 cm for 1990, 1991, 1992, 1993, and 1994, respectively.

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[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA-ARS.

Table 1. Monthly and annual precipitation at the study site (Akron, CO) from 1989 through 1994, and the 87-yr average precipitation.

Year	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
							cm						
1989	1.4	1.2	0.5	1.3	2.4	11.0	4.6	8.4	2.5	0.6	0.0	0.5	34.4
1990	1.9	0.4	4.3	3.8	10.4	2.4	12.0	11.2	1.8	2.7	2.0	0.2	53.0
1991	0.2	0.4	2.8	2.1	10.4	5.6	7.7	2.6	0.3	1.0	3.7	2.2	38.9
1992	1.4	0.5	5.0	0.5	3.8	9.8	5.1	10.2	0.1	2.1	1.9	0.6	40.9
1993	0.6	1.4	1.2	4.9	2.6	4.4	12.2	2.3	2.1	9.4	2.6	1.2	45.0
1994	1.0	0.5	0.2	6.1	2.2	0.6	6.9	3.0	1.1	7.0	2.6	1.3	32.5
87-yr Avg.	0.8	0.9	2.1	4.3	7.6	6.3	6.9	5.2	3.1	2.3	1.4	1.1	41.9

Winter Wheat

Other research has shown that soil water at planting, when using NT fallow management, may be similar for WF and WCF even though the fallow storage period is 4 mo shorter in the WCF rotation (Farahani et al., 1998). This was generally true for our situation, except for the 1992 crop when WF (NT) stored 8 cm more soil water during fallow than the WCF (NT) rotation (Table 2). The additional soil water with WF (NT) compared with WCF (NT) probably resulted from the storage of the above-average precipitation in July and August 1990 (Table 1) following harvest of the winter wheat crop in the WF (NT) system, whereas the 1990 corn crop in WCF (NT) system used this precipitation for grain production. The fallow period for WCF (NT) started in October 1990 with a relatively dry winter period (fall 1990 to spring 1991) and below-average precipitation (Table 1) in the summer of 1991 before wheat planting. Thus, the WCF (NT) soil profile did not get completely recharged, whereas the WF (NT) soil profile was fully recharged. As would be expected, the WF (BF) tended to have the least stored water although it was not significantly less in all years. These differences in total soil water at planting between treatments across years resulted in a significant year × treatment interaction.

Soil NO_3–N levels at wheat planting were generally high for all crop years (Table 2). Soil NO_3–N varied with year and between tillage and rotation treatment, resulting in a significant year × treatment interaction (Table 2). The available soil NO_3–N at planting plus the addition of 56 kg N ha^{-1} just before planting provided adequate N for the wheat yields obtained in this study. By 1994, the WCF (NT) and WF (NT) treatments were showing trends of less residual soil NO_3–N in the profile than the other treatments at wheat planting (Table 2). This probably reflects the sequestration of N in the crop residues and a slower release of residue N back into the soil as residual NO_3–N.

Wheat yields were not significantly affected by tillage or cropping system during this study (Table 3). Averaged over all tillage and cropping treatments, wheat grain yields varied between years. Wheat yields in 1990 with a medium level of available water supply at planting were lower than expected because of frost on 29 through 30 April and on 2, 4, 9, and 10 May plus hail on 14 June, followed by extremely high temperatures the last 10 d of June. Yields in 1994 diminished because of dry conditions during the later part of the wheat growing season and grain fill period. The grain yields for the WF (NT), WF (RT), and WF (CT) treatments (Table 3) reflect the same yield trends as those reported by Halvorson et al. (1994b) for the period 1987 through 1992 of this study.

If we plot wheat grain yield for all tillage–rotation combinations as a function of total water supply (soil water use + growing season rainfall) for 4 yr of this study (Fig. 1), we see that even the WF (BF) tillage system resulted in yields similar to those of the best water conservation systems. The water conservation made possible by NT and RT did not result in concomitant improvement in WF grain yield. The low grain yields in 1990—the year of frost, hail damage, and medium level of available water supply at planting—were omitted from the analysis in Fig. 1.

Total wheat biomass production (grain + straw) at harvest was not significantly affected by tillage or cropping system, with yields, averaged over years, of 7590, 8230, 7580, 8280, and 7670 kg ha^{-1} for the WCF (NT), WF (NT), WF (RT), WF (CT), and WF (BF) treatments, respectively. Total biomass production varied by year, with yields of 8870, 9760, 6260, 9080, and 5370 kg ha^{-1} for 1990, 1991, 1992, 1993, and 1994, respectively. Biomass production in 1990, 1991, and 1993 was significantly greater than in 1992 and 1994. Biomass production in-

Table 2. Total soil water content at wheat planting, soil water use by wheat, and soil NO_3–N at wheat planting for each tillage and rotation treatment at Akron, CO.

	Wheat crop year					
Treatment†	1990	1991	1992	1993	1994	Average
	— Total soil water at wheat planting, cm 180 cm^{-1} —					
WCF(NT)	42a‡	46a	38bc	45a	44a	43
WF(NT)	41a	42a	47a	48a	42a	44
WF(RT)	36b	43a	42ab	46a	41a	42
WF(CT)	37b	43a	43a	46a	40ab	42
WF(BF)	37b	40a	38c	47a	34b	39
Yearly avg.	39	43	42	46	40	
	— Soil water use by wheat, cm 180 cm^{-1} —					
WCF(NT)	16	18	13	24	17	18a
WF(NT)	16	12	18	24	15	17a
WF(RT)	12	16	16	22	14	16ab
WF(CT)	13	15	14	23	14	16ab
WF(BF)	12	11	14	26	9	14b
Yearly avg.	14b§	15b	15b	24a	14b	
	— Soil NO_3–N at what planting, kg ha^{-1} 180 cm^{-1} —					
WCF(NT)	120a	180a	225a	214b	80c	164
WF(NT)	162a	262a	109b	370a	88bc	198
WF(RT)	158a	236a	119b	208b	154a	175
WF(CT)	144a	189a	112b	187b	136abc	154
WF(BF)	176a	179a	167ab	247b	143ab	183
Yearly avg.	152	210	146	245	120	

† WCF, wheat–corn fallow; NT, no-till; WF, winter what–fallow; RT, reduced till; CT, conventional till; BF, bare fallow.

‡ Values within a column followed by the same letter are not significantly different.

§ Average yearly values within a row followed by the same letter are not significantly different.

Table 3. Winter wheat grain yields and residue levels as a funciton of tillage and crop rotation from 1990 through 1994 at Akron, CO.

Treatment†	Year of wheat harvest					Average
	1990	1991	1992	1993	1994	
	Wheat grain yield, kg ha^{-1}					
WCF(T)	1961	3725	2255	3960	2420	2864a†
WF(NT)	2130	3959	2994	3934	2594	3122a
WF(RT)	1783	3949	2999	3841	2100	2934a
WF(CT)	2073	3968	2542	4037	2254	2975a
WF(BF)	1649	3839	2208	4071	2099	2773a
Yearly avg.	1919c‡	3888a	2600b	3969a	2293bc	
	Wheat straw residue, kg ha^{-1}					
WCF(NT)	7017	5943	2963	4603	3277	4760a
WF(NT)	7780	6296	3164	5228	3318	5157a
WF(RT)	6955	4539	4294	4869	2838	4699a
WF(CT)	7454	6308	4345	5452	3186	5349a
WF(BF)	5842	6767	3472	5372	3230	4937a
Yearly avg.	7010a	5971b	3648d	5105c	3170d	

† WCF, wheat–corn–fallow; NT, no-till; WF, winter wheat–fallow; RT, reduced till; CT, conventional till; BF, bare fallow.

‡ Values within a column followed by the same letter are not significantly different.

§ Average yearly values within a row followed by the same letter are not significantly different.

creased with increasing level of water supply (soil water use + growing season precipitation) as shown in Fig. 2 similar to grain yields (Fig. 1). Thus, crop residue returned to the soil increased as water supply increased. The 1990 total biomass data is omitted from the regression analysis in Fig. 2 because of the frost and hail damage that occurred in that year.

An important aspect of tillage and rotation interactions is the amount of crop residue remaining on the soil surface because of its combined effects on soil water conservation and soil erosion control. In our case, the amount of wheat residue returned to the soil surface at harvest was not significantly affected by tillage or cropping system treatment (Table 3), and there was no significant year × treatment interaction. Wheat residue amount returned to the soil (averaged over all systems) varied by year. Residue amounts by year were in the order 1990 > 1991 > 1993 > 1992 = 1994.

Corn

The WCF (NT) rotation had significantly larger corn grain yields than the CC (NT) rotation every year except 1990 (Fig. 3). The above-average precipitation during the 1990 corn growing season resulted in the highest yields during the 5-yr study and permitted the CC (NT) rotation to produce a high yield relative to WCF (NT). Lower yields were associated with lower amounts of growing season precipitation, as noted for 1991 and 1994. Corn in the WCF (NT) rotation averaged 3520 kg ha^{-1} while CC (NT) averaged only 1980 kg ha^{-1}. This large difference in average yield was observed even though the average total soil water content of the 180-cm soil profile at corn planting in the CC (NT) rotation (39 cm) did not differ from the soil water content in the WCF (NT) rotation (40 cm). There were no significant differences in planting soil water between CC (NT) and WCF (NT) in any year. Soil water at corn planting in 1992 (42 cm), 1993 (40 cm), and 1994 (42 cm) was greater than in 1990 (38 cm) and 1991 (36 cm). As can be observed in Fig. 4, corn grain yield response to each increment of water supply (growing season precipitation + soil water use) in the CC (NT) rotation was double that of the WCF (NT) system. Because the soil water at planting did not differ between rotations, we expected corn yields

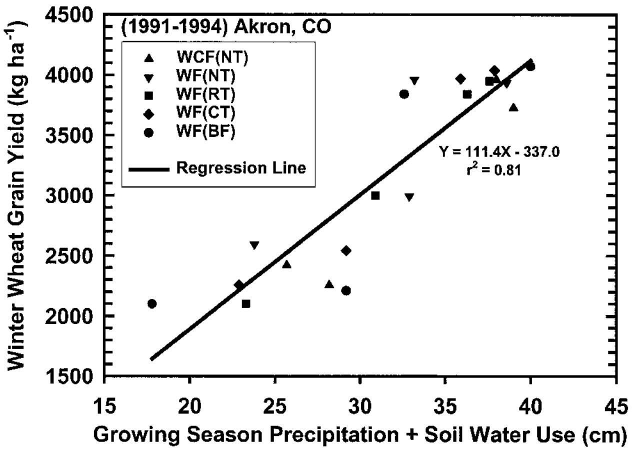

Fig. 1. Winter wheat yields from 1991 through 1994 as a function of growing season precipitation plus soil water use from the 0- to 180-cm profile for the wheat–corn–fallow (WCF) and wheat–fallow (WF) no-till (NT), reduced-till (RT), conventional-till (CT), and bare-fallow (BF) treatments.

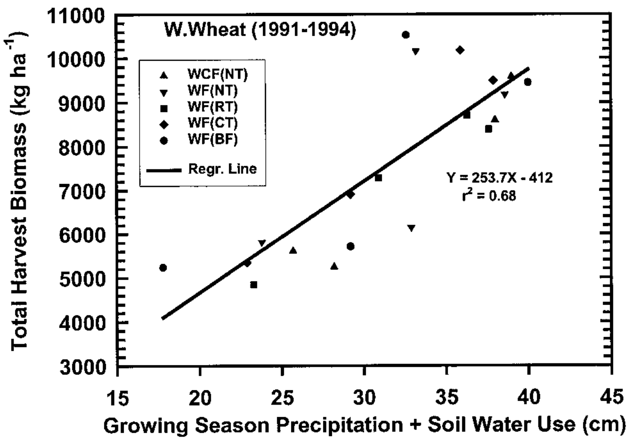

Fig. 2. Winter wheat total biomass (grain + straw) at harvest from 1991 through 1994 as a function of growing season precipitation plus soil water use from the 0- to 180-cm profile for the wheat–corn–fallow (WCF) and wheat–fallow no-till (NT), reduced-till (RT), conventional-till (CT), and bare-fallow (BF) treatments.

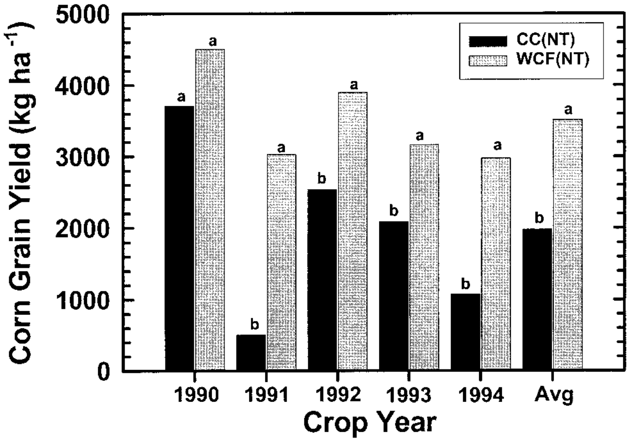

Fig. 3. Corn grain yield each crop year in the continuous-corn (CC) and wheat–corn–fallow (WCF) rotations under no-till (NT). Yields within a year with the same letter on top of the bar are not significantly different.

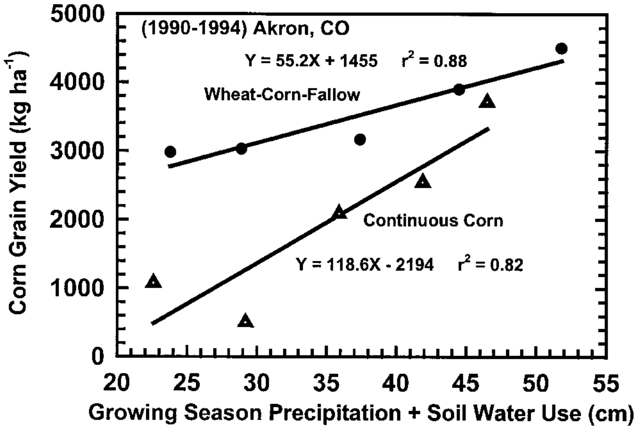

Fig. 4. Corn grain yields from 1990 through 1994 as a function of growing season precipitation plus soil water use from the 0- to 180-cm profile for the wheat–corn–fallow and continuous-corn rotations.

in both rotations to be a function of growing season precipitation and to have equal responses to each increment of available water. The heavy weed infestation in the CC (NT) plots in 1991 (a relatively dry year, Table 1) probably contributed to the low CC (NT) grain yields in 1991; thus, the slope of the line in Fig. 4 is steeper than would be expected. Visually, weed intensity was more severe in the CC (NT) rotation late in the season compared with a nearly weed-free environment in the WCF (NT). Weed pressure was greater in dry years. Soil water use by corn averaged 7 and 9 cm for the CC (NT) and WCF (NT) treatments, respectively, when averaged over years and was not significantly different. Soil water use by corn in 1990 (8 cm), 1991 (10 cm), 1992 (12 cm), and 1994 (9 cm) was greater than in 1993 (3 cm). Corn stands were uniform between treatments and did not contribute to the yield differences. Soil NO_3–N at corn planting was 43, 64, 115, 63, and 97 kg ha^{-1} NO_3–N in the CC (NT) system and 161, 82, 100, 88, and 90 kg ha^{-1} NO_3–N in the WCF (NT) in 1990, 1991, 1992, 1993, and 1994, respectively. These soil NO_3–N levels plus the addition of 84 kg N ha^{-1} to the corn crop provided sufficient available N to achieve yields higher than those obtained in this study.

Corn residue returned to the soil at grain harvest was significantly greater in the WCF (NT) rotation (4110 kg ha^{-1}) than for CC (NT) (3190 kg ha^{-1}). Corn residue returned to the soil also varied with year, with amounts of 4150, 4730, 3210, 2820, and 1020 kg ha^{-1} for 1990, 1991, 1992, 1993, and 1994, respectively. The lowest residue level occurred in 1994, the driest year of the study. Total crop residue returned to the soil in the WCF (NT) rotation was 4110 kg ha^{-1} from the corn phase and 4760 kg ha^{-1} from the wheat phase, totaling 8870 kg ha^{-1} residue in each 3-yr cycle, which is an annualized amount of 2960 kg ha^{-1}. Annualized residue return in WF tillage systems averaged 2520 kg ha^{-1}, which is 15% less residue return to the soil than with WCF (NT) (Table 4).

Surface Crop Residue at Planting

At wheat planting, the greatest amount of surface crop residue was found in the WCF (NT) rotation, generally followed by the WF (NT) and WF (RT) treatments, but the actual amount varied with year (Fig. 5). The WF (BF) treatment always had the least quantity of surface crop residue. Surface crop residues in the WCF (NT) treatment appeared to be greater with the passage of time as evidenced by the 1993 and 1994 data relative to earlier years. We anticipate that surface residues will accumulate during early years after conversion to NT and especially in rotations that include corn.

Table 4. Annualized grain yields, crop residue, and organic C returned to soil in aboveground biomass as a funciton of crop rotation and tillage treatment in the long-term tillage experiment at Akron, CO.

Rotation†	Tillage‡	Annual grain yield§	Grain yield relative to WF	Annual residue return to soil	Annual C return to soil¶	C input relative to WF
		kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}	%
WF	NT	1560		2580	1160	
	RT	1470		2350	1060	
	CT	1490		2670	1200	
	BF	1390		2470	1110	
	Mean	1480		2520	1130	
WCF	NT	2130	144	2960	1330	118
CC	NT	1980	134	3190	1440	127

† WF, winter wheat–fallow; WCF, wheat–corn–fallow; CC, continuous corn.

‡ NT, no-till; RT, reduced till; CT, conventional till; BF, bare fallow.

§ Annualized grain yields or residue returned to soil were calculated by summing total grain or residue produced in the rotation and dividing by the number of years in the rotation.

¶ Carbon returned to the soil was calculated by assuming the crop residue was 45% C.

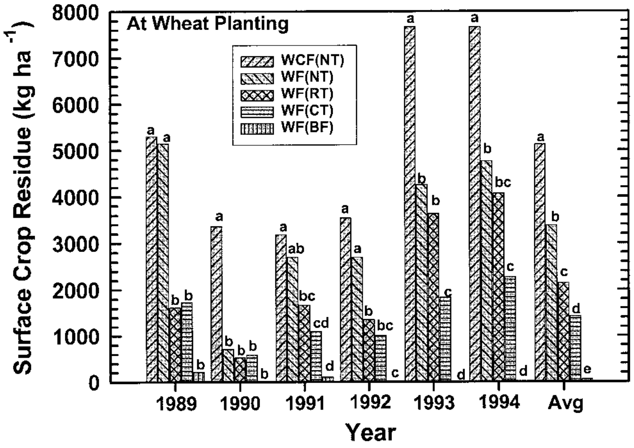

Fig. 5. Surface crop residue level at winter wheat planting in September from 1989 through 1994 for the wheat–corn–fallow (WCF) and wheat–fallow (WF) no-till (NT), reduced-till (RT), conventional-till (CT), and bare-fallow (BF) treatments. Residue levels within a year with the same letter on top of the bar are not significantly different.

Peterson et al. (1998) report that NT systems where corn was included in the rotation had more of their total C remaining in the crop residue fraction than did WF (NT) systems. They surmised that the relatively large corn stalks did not decompose as rapidly as wheat straw. Corn stalks and corn cobs from previous years were visible in the corn rotations in this study. Averaged across years, WCF (NT), WF (NT), and WF (RT) treatments all had more than 2000 kg ha^{-1} surface residue at wheat planting, which will effectively reduce wind erosion (Fenster et al., 1977; Fryrear, 1985). The WF (CT) and especially the WF (BF) treatments with low amounts of residue are susceptible to wind and water erosion.

For the most part, surface residue levels at corn planting were equal in the WCF (NT) and CC (NT) rotations with some annual variations as shown in Fig. 6. In 1990, surface residue at corn planting was greater in CC (NT) than in WCF (NT); there were no differences in residue levels between rotations in 1991 and 1992, but by 1993 and 1994, WCF (NT) had greater amounts of surface residue at planting than did CC (NT). Because much of the corn residue is standing after harvest, 4000 kg ha^{-1} of corn residue should provide adequate protection for erosion control (Fryrear, 1985).

Soil Organic Carbon

Soil organic C concentration was measured in 1989 when the current tillage and rotation treatments were updated and/or initiated using soil sample depths of 0 to 5, 5 to 10, and 10 to 20 cm. At that time, there were no differences in SOC concentration due to management treatment. The SOC concentration averaged 9.23, 7.58, and 6.93 g C kg^{-1} soil for the 0- to 5-, 5- to 10-, and 10- to 20-cm soil depths, respectively, on 14 Apr. 1989. Soil bulk density was not determined at that date; thus, we are not able to accurately calculate the SOC mass present at each soil depth in 1989.

By 1994, SOC levels in the 0- to 7.6-cm depth had responded differentially to the tillage and rotation treatments such that CC (NT) had the highest SOC level and WF (BF) the lowest (Fig. 7). Soil organic C levels in descending order were CC (NT) ≥ WCF (NT) ≥ WF (NT) = WF (RT) = WF (CT) > WF (BF). Tillage and rotation treatments had not affected SOC in the 7.6- to 15.2-cm soil depth. Combined over the 0- to 15.2-cm depth, differences in SOC mirrored those found in the surface 0- to 7.6-cm depth, with the maximum amount in the CC (NT) treatment and the least amount in the WF (BF) treatment.

Although not significant at the 5% probability level, the CC (NT) treatment with no fallow period appears to be accumulating SOC faster than any treatment that included a summer fallow period, even more rapidly than WCF (NT), which has annualized C additions that

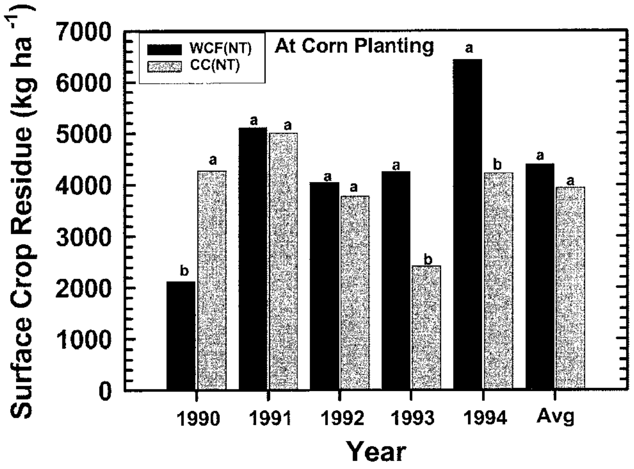

Fig. 6. Surface crop residue level at corn planting for the wheat–corn–fallow (WCF) and continuous-corn (CC) rotations under no-till (NT). Residue levels within a year with the same letter on top of the bar are not significantly different.

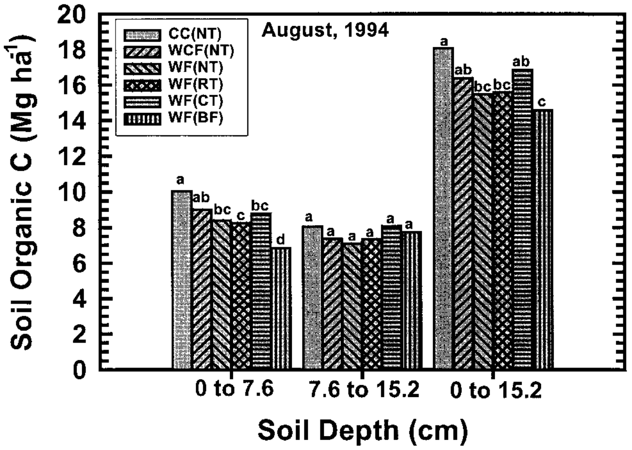

Fig. 7. Soil organic carbon (SOC) in August 1994 as a function of soil depth for the continuous-corn (CC), wheat–corn–fallow (WCF), and wheat–fallow (WF) no-till (NT), reduced-till (RT), conventional-till (CT), and bare-fallow (BF) treatments. Levels of SOC within a soil depth with the same letter on top of the bar are not significantly different.

are essentially the same amount (Table 4). These observations are supported by the work reported by Halvorson et al. (2002) in the northern Great Plains where SOC after 12 yr was similar for CT, RT, and NT in the WF system. They also found that SOC increased with decreasing tillage in the annual cropping system. Similar trends were reported by Bowman et al. (2002) in the central Great Plains where the annual cropping rotation without a fallow period had a higher level of SOC than the WF system.

As expected, the WF (BF) treatment that included a moldboard plow operation during the fallow period resulted in the lowest level of SOC, suggesting a greater loss of SOC from this system compared with any other treatment in the study. This is consistent with the observations reported by Peterson et al. (1998) for the Great Plains.

SUMMARY

Winter wheat grain yields and biomass production were not significantly affected by tillage system or crop rotation and varied only with yearly changes in climatic conditions and rainfall. As expected, grain yield and total biomass production increased with increasing amounts of available water supply. Wheat grain yields for all WF tillage systems and WCF (NT) were not significantly different. Corn grain yields usually were greater in the WCF (NT) rotation than in the monoculture CC (NT) rotation. Low yields were observed with the CC (NT) rotation, even with NT management. Based on this study, the CC (NT) rotation is probably not a viable option for the central Great Plains. The low corn yields for CC (NT) are consistent with those reported by Halvorson et al. (1994a) for 2-yr corn rotations that did not include a fallow period compared with WCF. Total wheat residue and estimated organic C returned to the soil surface were similar for each of the tillage and crop rotation treatments, but corn residue return was greater with WCF (NT) (4110 kg ha^{-1}) than with CC (NT) (3190 kg ha^{-1}). Surface crop residue at wheat planting decreased in the order: WCF (NT) (5120 kg ha^{-1}) > WF (NT) (3380 kg ha^{-1}) > WF (RT) (2140 kg ha^{-1}) > WF (CT) (1420 kg ha^{-1}) > WF (BF) (50 kg ha^{-1}). Soil erosion potential was minimal with WCF (NT), WF (NT), and WF (RT) systems. At corn planting, surface crop residue amounts did not differ for WCF (NT) and CC (NT) when averaged over years (4160 kg ha^{-1}) but did vary with year.

Soil organic C mass after 5 yr was greatest for the CC (NT) rotation and least with the WF (BF) treatment as would be expected. Reducing the amount of fallow in a rotation had a positive impact on SOC accumulation.

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