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Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C

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Abstract

Concern about soil organic matter losses as a result of cultivation has been voiced consistently since the early part of the 20th century. Scientists working in the US. Great Plains recognized that organic matter losses from an already small pool could have major negative consequences on soil physical properties and N supplying capacity. The advent of reduced- and no-till systems has greatly improved our ability to capture and retain precipitation in the soil during the non-crop periods of the cropping cycle, and has made it possible to reduce fallow frequency and intensify cropping systems. The purpose of this paper is to summarize the effects of reduced tillage and cropping system intensification on C storage in soils using data from experiments in North Dakota, Nebraska, Kansas, Colorado, and Texas. Decades of farming with the wheat (*Triticum aestivum* L.)–fallow system, the dominant farming system in the Great Plains, have accentuated soil C losses. More intensive cropping systems, made possible by the greater water conservation associated with no-till practices, have produced more grain, produced more crop residue and allowed more of it to remain on the soil surface. Combined with less soil disturbance in reduced- and no-till systems, intensive cropping has increased C storage in the soil. We also conclude that the effects of cropping system intensification on soil C should not be investigated independent of residue C still on the surface. There are many unknowns regarding how rapidly changes in soil C will occur when tillage and cropping systems are changed, but the data summarized in this paper indicate that in the surface 2.5 cm of soil, changes can be detected within 10 years. It is imperative that we continue long-term experiments to evaluate rates of change over an extended period. It is also apparent that we should include residue C, both on the surface of the soil and within the surface 2.5 cm, in our system C budgets if we are to accurately depict residue–soil C system status. The accounting of soil C must be done on a mass basis rather than on a concentration basis. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Concern about organic matter losses from soil as a result of cultivation has been voiced consistently since the early part of the 20th century (Stewart and Hirst,

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1914; Russel, 1929; Gainey et al., 1929; Salter and Green, 1933; Jenny, 1933; Hide and Metzger, 1939). Many of these scientists worked in the Great Plains where it was recognized that organic matter losses from an already small pool could have major negative consequences on soil physical properties and N supplying capacity.

Decades of farming with the wheat (*Triticum aestivum* L.)–fallow system, the dominant farming system in the Great Plains, have accentuated soil C losses. Haas et al. (1957) reported C losses of over 50% (C concentration basis) at many Great Plains sites after 30–40 years of cultivation in a wheat–fallow system with conventional tillage. Peterson and Vetter (1971), using total soil N as an index, reported that wheat–fallow systems had organic N losses of 20% to 30% (mass basis). Based on changing C:N ratios when soils are cultivated, these N losses would compare to C losses of about 40%. Despite the negative effects on C, the crop–fallow agroecosystem has remained attractive to producers through the 1990s because it stabilizes short term production, provides short-term sustainability, and farm program regulations have favored it. Evidence of its negative influence on soil and environmental quality continues to build, and even its economic advantage seems to be lessening with the combination of high production costs and low grain market prices. Dhuyvetter et al. (1996) show that if government deficiency payments were not available, the wheat–fallow systems would not be profitable. Furthermore, the improved water capture possible with no-till does not result in much improvement in wheat yields within a wheat–fallow system. In fact wheat–fallow is even less profitable with no-till than with tillage.

Soil cultivation stimulates soil C loss because it accelerates oxidation of soil C by microbial activity. Tillage reduces aggregate size and exposes new aggregate surfaces to microbial attack, which stimulates oxidation. When cultivation removes surface cover, it exposes surface soils to more extensive erosion and this accelerates removal of the C rich surface soil. The practice of fallowing decreases C inputs to the soil, when compared to the native prairie situation and even when compared to continuous cropping. Wheat grown after fallow has a greater grain to stover ratio than wheat grown continuously and thus, proportional to each unit of grain produced, less stover C is returned to the soil in wheat after fallow. The improved soil water conditions following fallow improve the chances of having some available water present during grain fill, which increases the grain to stover ratio. So, wheat produced in tilled fallow systems accelerates C oxidation, encourages C removal by erosion, and adds much less C to soils than occurred under prairie conditions. Through the 1950s and 1960s little new work on soil organic C was conducted, and little progress was made in conservation of soil C, but in the mid-1960s research in no-till systems was begun, which set the stage for present day work.

The advent of reduced- and no-till systems greatly improved our ability to capture and retain precipitation in the soil during the non-crop periods of the cropping cycle. These improvements in water conservation have made it possible to reduce the frequency of fallow and intensify cropping systems relative to wheat–fallow. Smika and Wicks (1968) provided clear-cut evidence that no-till practices result in improvements in water conservation that permit at least two crops in a three year time frame. Peterson et al. (1996) document that with no-till, intensified cropping is possible from Texas to North Dakota in the Great Plains region.

The more intensive cropping systems, relative to wheat–fallow, not only produce more grain per unit of water, but produce and leave more crop residue on the soil surface. Combined with less soil disturbance in reduced- and no-till systems, the possibility for storing C in the soil under more intensive cropping is greatly increased. The purpose of this paper is to summarize the effects of reduced tillage and cropping system intensification on C storage in soils. Data from experiments in North Dakota, Nebraska, Kansas, Colorado, and Texas will be used.

2. Discussion and interpretation of available data

Evaluation of soil C data requires agreement on a standard of comparison. Most data available in the literature, like those of Haas et al. (1957), report only soil C concentration and the changes that occurred in that variable. There was little recognition that soil bulk density also changes upon conversion of grassland to cultivated land. Therefore the actual C loss may be quite different from losses shown by decreased C

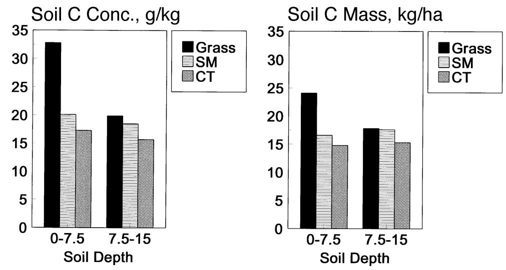

Fig. 1. Soil C content of two soil depths evaluated by concentration and by weight and as affected by stubble mulch (SM) and conventional wheat–fallow (CT) tillage systems (Bauer and Black, 1992).

concentrations. Because the bulk density of the surface soil in a prairie sod is often <1.0 Mg m^{-3} (0–10 cm), and the density of cultivated surface soils usually is 1.2–1.3 Mg m^{-3}, C losses calculated on a mass basis are less than those reported on a concentration basis. Bauer and Black (1992) published soil C and bulk density data for two soil horizons under grassland, stubble mulch and conventional till wheat–fallow systems. Their data provide a vivid comparison of the differences between C losses calculated on a concentration basis versus a mass basis. Carbon loss from the 0–7.5 cm soil horizon on a C concentration basis was 48% when grassland was compared to the conventional till wheat–fallow system (Fig. 1). Carbon loss on a mass basis was 39% for the same treatment comparison. Obviously C losses were large based on either evaluation, but in an effort to be quantitative, the weight basis seems best. Method of C loss assessment made less difference in the 7.5–15 cm depth because bulk density differences between grassland and cultivated soils were smaller, but the weight method was still most conservative. Therefore, throughout our data evaluation process, we use the C mass basis. The reader should be aware, however, that since all soil samples were collected to a constant depth, and since bulk density could differ, the soil mass involved in a C weight calculation is not necessarily constant.

Our analysis will first address effects of tillage system on C storage, followed by an evaluation of cropping system intensification effects under specific tillage regimes. For brevity, only subsets of the data are shown, but references are given where results and statistical analyses are fully described.

2.1. Tillage effects

Lyon et al. (1996) compared the effects of no-till, stubble mulch, and plow fallow management in a long-term winter wheat–fallow system experiment at Sidney, NE. The site was taken from native grass at experiment initiation in 1970, has nearly level topography, and therefore has had essentially no water erosion. There have been two overflow events that may have deposited small amounts of silt. Wind erosion possibilities also are limited because of the narrow strips created by the experimental design and the fact that the experiment is surrounded by grass pasture. This study allows a comparison of tillage effects on soil C with limited influence of erosion. It also is one of the few sites in existence with a native grass control built into the experimental design.

Decreasing tillage (plow to stubble mulch to no-till) resulted in less soil C losses in the winter wheat–fallow system (Table 1). Carbon losses from 1970 until 1990 for the no-till, stubble mulch and plow tillage systems were 4500, 6900 and 11 200 kg ha^{-1}, respectively. For the first 12 years, C losses from no-

Table 1
Effects of tillage system on soil C content in the surface 20 cm at various times after sod breaking at Sidney, NE (See Lyon et al., 1996)

Year	Tillage system			
	Native sod	No-till	Stubble mulch	Plow
	kg ha^{-1}			
1970	41 300	—	—	—
1982 [a]	41 800	37 200	35 900	33 000
1990 [b]	42 400	37 300	34 900	30 600

[a] Lamb et al., 1985.
[b] Cambardella and Elliott, 1992.

Table 2
Effects of tillage system on soil C change in the surface 20 cm relative to the native sod at various times after sod breaking at Sidney, NE (See Lyon et al., 1996)

Year	Tillage system			
	Native sod	No-till	Stubble mulch	Plow
	% of Native sod			
1970	100	—	—	—
1982 [a]	100	89	86	79
1990 [b]	100	89	83	73

[a] Lamb et al., 1985.
[b] Cambardella and Elliott, 1992.

till managed soil were about 11% of that for the native sod with no additional C loss from 1982 to 1990 (Table 2). However, stubble mulch and plow tillage systems continued to lose small amounts of C from 1982 to 1990. From 1982 until 1990 the no-till, stubble mulch and plow tillage systems lost 0, 1000 and 2400 kg ha^{-1} of C, respectively. These data provide evidence that reducing tillage promotes C retention in soils. The various tillage systems in this experiment have had essentially equal residue additions annually since 1970. Fallow tillage effects on grain yield have varied with years. In most years, no differences were observed. Among years when differences were observed, no consistent treatment effects were evident. Downy brome (*Bromus tectorum* L.) infestations in the no-till occasionally reduced grain yields compared to stubble mulch or plow fallow. In those years residue additions to no-till were still equivalent to that for the other two treatments.

Halvorson et al. (1996) compared the effects of conventional till and no-till on soil C in a winter wheat–fallow system at Akron, CO. The site had been cultivated since sod breaking in 1907. From 1907 to 1954 the area was used for various crop rotation experiments, and then in 1955 the entire area was cropped to grain sorghum [*Sorghum bicolor* (L.) Moench]. From 1956 to 1966 the area was uniformly cropped to winter wheat–fallow with stubble mulch tillage. In 1967 the tillage experiment was established. This experiment is slightly older than the Sidney, NE site, and shares the stubble mulch and no-till treatments, but does not have a plow fallow. It also differs from Sidney in that the soil had been cultivated for over 60 years before the treatments were established. Estimates made from a nearby tract of native sod of the same soil type indicate that the surface 20 cm of this soil contained 36 000–40 000 kg of C ha^{-1} before cultivation began in 1907.

After 15 years of stubble mulch and no-till, the surface 20 cm of soil had 1850 kg ha^{-1} more C with no-till than with stubble mulch (Table 3). The difference is probably a result of C gains in the no-till, coupled with continued losses from the stubble mulch. Compared to the native condition with its estimated 36 000–40 000 kg ha^{-1} of C, the stubble mulch treatment has less than 50% of the native soil C content.

Table 3
Soil C in the surface 20 cm of soil as affected by tillage system at Akron, CO. (Sampled in 1982 after 15 years of treatment application) (See Halvorson et al., 1996)

Tillage system					
Stubble mulch		No-till		Means	
North [a]	South [a]	North	South	Stubble mulch	No-till
kg ha^{-1}					
19 630	15 620	20 760	18 190	17 630	19 480

[a] North side of wheat–fallow experiment in crop in odd years and South side in crop in even years.

Table 4
Annualized winter wheat residue and grain production as affected by tillage system at Akron, CO (Mean of 13 years of data) (See Halvorson et al., 1996)

Production	Tillage system		
	Stubble mulch	Reduced tillage	No-till
	kg ha^{-1}		
Residue	3400	3360	3320
Grain	1480	1420	1400

No-till had slightly more than 50% of the native C level by 1982; indicating it may have gained C at a faster rate than did the stubble mulched soil.

The C increases observed for no-till have not occurred because of increased productivity under no-till. The three systems, stubble mulch, reduced-till, and no-till, each produced essentially the same amounts of crop residue and grain (Table 4). Thus the greater C content for the no-till soil resulted from a slower C oxidation rate in these soils.

Jones et al. (1996), working at Bushland, TX in a high potential ET environment, compared stubble mulch and no-till in an experiment established on graded terraces in 1949. Originally the experiment only had stubble mulch tillage in a wheat–sorghum–fallow rotation. A no-till treatment was added in 1981 within the same rotation. A second experiment with tillage systems and rotations was started on mini-benches in 1982. Soil C measurements were made in 1988 and 1989 on these experiments, respectively. No initial soil C analyses are available for the graded terrace experiment. However, Unger et al. (1990) report that the 0–7.5 cm soil layer in the minibench experiment contained 10.3 g kg^{-1} at initiation in 1982, which is equivalent to 9560 kg C ha^{-1} in that layer.

Table 5
Soil C in the graded terrace experiment in 1988 as related to stubble mulch tillage and no-till treatments at Bushland, TX (See Jones et al., 1996)

Depth	Tillage method	
	Stubble mulch [a]	No-till [b]
cm	kg ha^{-1}	
0–1	1290	1700
1–2	1330	1700
2–4	2830	2910
4–6	2670	2550
6–8	2630	2500
8–10	2520	2550
Total	13 270	13 910

[a] Stubble mulch used since 1949.
[b] No-till started in 1981.

These data allow comparison of tillage and crop rotation effects on soil C, but cannot be used to determine if C storage is increasing because there is no complete baseline C data for the sites prior to treatment initiation. The minibench experiment allows comparison of both crop rotation and tillage effects. No-till soils obviously have more C than stubble mulch soils in both experiments, independent of crop rotation (Tables 5 and 6). One cannot determine if the difference due to tillage results from slower losses under no-till compared to stubble mulch, or if stubble mulch is static and no-till is increasing in C content. This is similar to the situation for the Akron, CO data. Results from the graded terrace experiment indicate a definite C difference in the surface 2 cm of soil under no-till relative to stubble mulch, but the total C in the

Table 6
Soil C in the minibench experiment as related to tillage system and crop rotation at Bushland, TX (See Jones et al., 1996)

Depth	Crop rotation							
	Cont. sorghum		Cont. wheat		Wheat–sorg–fallow		Wheat–fallow	
	SM [a]	NT [b]	SM	NT	SM	NT	SM	NT
cm	kg ha^{-1}							
0–7.5	6420	8100	6710	8700	6490	8080	6980	8440
7.5–15	6950	7210	8030	7350	6950	7180	7740	7170
0–15	13 370	15 310	14 740	16 050	13 440	15 260	14 720	15 610

[a] SM=stubble mulch.
[b] NT=no-till (Soil C in the 0–7.5 cm depth was 9560 kg ha^{-1} in 1982, when the experiment was established).

surface 10 cm of soil differs by only 640 kg ha^{-1} (Table 6). In the latter case, the no-till had been in place only 7 years at the time of sampling. It does appear, however, that all systems in the minibench experiment have lost C since 1982 because the C content of the surface was 9560 kg ha^{-1} then, and now all systems are below 8700 kg ha^{-1}.

Reduction in soil disturbance from conventional, highly disturbed, tillage methods to reduced- or no-till practices increases the amount of C stored in a soil and/or slows C losses. Data from Nebraska, Colorado, and Texas all support this conclusion. Data from Sidney NE, Table 1, shows that a soil plowed from sod in 1970 lost over 8000 kg C ha^{-1} in the first 12 years under plowed fallow and then lost an additional 2400 kg C ha^{-1} in the following 8 years. Recall that this is a site where erosion would play a minor role in C loss. In this same time frame, soil under no-till management lost about 4000 kg C ha^{-1} in the first 12 years, and then remained stable over the next 8 years. No-till soil at Akron, CO had over 2200 kg ha^{-1} more C than stubble mulch soil 15 years after treatment initiation. At Bushland, TX no-till soil had 650 kg ha^{-1} more C than stubble mulch soil after 8 years of no-till, and in another experiment C in no-till soil exceeded that in stubble mulch soil by 1500 kg ha^{-1} after 7 years.

Conversion to no-till conserves soil C and may even allow it to accumulate relative to stubble mulch and plow tillage. It would appear that converting to no-till systems would allow sequestration of C relative to the tillage systems that currently predominate in dryland areas.

2.2. Cropping system effects

The added water conserved in no-till systems has made it possible to use more intensive cropping systems relative to wheat–fallow, as was noted in the introduction of this paper. Hypothetically, intensifying cropping systems relative to wheat–fallow should add more C to soils because more C is photosynthetically fixed in these systems. Coupled with the minimum disturbance of no-till soils, the overall effects of intensification on C storage in soils should be significantly positive.

Black and Tanaka (1996) compared spring wheat–fallow versus continuous cropping (spring wheat–winter wheat–sunflower [*Helianthus annuus* L.]) under three tillage regimes: no-till, minimum till, and conventional till. Minimum till was a combination of sweep operations and herbicides for weed control. Conventional tillage weed control used sweeps and tandem discing with no herbicidal weed control. The experiment also had N rates embedded in each tillage and cropping system. For this analysis, data from the highest N rate was used because, based on grain yield, this rate appeared to provide optimum conditions for plant growth.

Table 7
Annualized grain yield (all crops in a given system) as affected by cropping system and tillage system (optimum N fertilization) at Mandan, North Dakota (Mean of 8 years of data) (See Black and Tanaka, 1996)

Cropping system	Tillage system		
	Conv. till	Mulch till	No-till
	kg ha^{-1}		
Spring wheat–fallow	1160	1180	1160
Spring wheat–winter wheat–sunflower	1500	1640	1730
Change due to cropping intensification	+340	+460	+570

With conventional tillage, continuous cropping increased grain yield about 30% compared to alternate crop–fallow (Table 7). With no-till, grain yield in the continuous cropping treatment was increased by more than 45% compared to spring wheat–fallow. Residue production, the major source of C returned to the soil, was increased by 54%, 72%, and 88% by conversion to continuous cropping compared to alternate crop–fallow for conventional, minimum, and no-till treatments, respectively (Table 8).

In this same study (Black and Tanaka, 1996) soil C contents under alternate crop–fallow generally declined from 1983 to 1991 (Table 9). Interestingly, soil C content for the conventional tillage system remained near the 1983 value. This treatment resulted in loss of C in the surface 7.5 cm but a gain of C in the 15–30 cm zone. There is no apparent reason for the gain in C in the lower depth increment. Under minimum and no-till, soil C contents declined in all zones. By 1991, soil C contents for conventional, minimum, and no-till in the spring wheat–fallow system were +2%, −8%, and −13%, respectively, relative to the

Table 8
Annualized residue production as affected by cropping system and tillage system (optimum N fertilization) at Mandan, North Dakota (Mean of 8 years of data) (See Black and Tanaka, 1996)

Cropping system	Tillage system		
	Conv. Till	Mulch till	No-till
	kg ha^{-1}		
Spring wheat–fallow	1820	1800	1790
Spring wheat–winter wheat–sunflower	2820	3100	3370
Change due to cropping intensification	+1000	+1300	+1580

1983 levels. Continuous cropping with conventional tillage decreased soil C by 2.5%, but increased it by 5.6% and 10.1% for minimum and no-till, respectively. By 1991, under conventional tillage, continuous cropping plots had 2900 kg ha^{-1} less soil C than did alternate crop–fallow plots. However, under minimum and no-till, continuous cropping plots had 9300 and 15 600 kg ha^{-1} more soil C than did alternate crop–fallow plots. The continuous cropping system under minimum and no-till appeared to store more C in the lower portions of the surface horizon than occurred with these same tillages in an alternate crop–fallow system.

Within the minibench experiment cited earlier, Jones et al. (1996) compared the effects of continuous cropping systems with monoculture wheat and sorghum to those for winter wheat–sorghum–fallow (WSF) and winter wheat–fallow (WF) (Table 6). They reported little difference in soil C due to cropping system after 7 years of use. For example, no-till continuous wheat had the greatest total C content of all treatments, but it was only about 400 kg ha^{-1} greater than no-till wheat–fallow. With the variability possible in soil C measurements, it is not likely that this is a significant difference.

Havlin and Kissel (1996) compared rotations comprised of: (i) continuous soybean (*Glycine max* L.), (ii) continuous grain sorghum, and (iii) sorghum–soybean using both conventional tillage (fall chisel plow followed by disc) and no-till. The experiment was initiated in 1975 and soils were sampled for C analysis in 1986 (data not shown). Grain yields of both soybean and grain sorghum were improved in the soybean–sorghum rotation compared to those for monoculture of either plant. Amounts of residues returned to the soil were calculated using typical grain:stover ratios

Table 9
Soil C contents in 1983 and 1991 as affected by cropping and tillage systems at Mandan, North Dakota (See Black and Tanaka, 1996)

Cropping system	1983 Soil C		1991 Soil C		
			Tillage system		
	Depth	Initial	Conv. till	Mulch till	No-till
	cm	kg ha^{-1}			
Spring wheat–fallow	0–7.5	18 460	17 160	16 500	16 020
	7.5–15	20 450	20 500	19 240	16 932
	15–30	27 710	30 190	25 340	24 750
	Total	66 620	67 850	61 080	57 702
Spring wheat–winter wheat–sunflower	0–7.5	18 460	18 530	19 070	2 0356
	7.5–15	20 450	19 700	19 250	20 436
	15–30	27 710	26 700	32 030	32 576
	Total	66 620	64 930	70 350	73 367
Change due to cropping intensification from 1983 to 1991	0–7.5		+1370	+2570	+4336
	7.5–15		−800	+10	+3504
	15–30		−3490	+6690	+7826
	Total		−2920	+9270	+15665

for each crop. Soil C weight per hectare was directly related to the amount of crop residue returned to the soil. Under no-till management, each Mg ha^{-1} of residue returned to the soil increased soil C by 1.52 g kg^{-1}. The highest residue crop, grain sorghum, increased soil C the most, and thus the continuous grain sorghum rotation impacted soil C more than the other rotations.

Peterson and Westfall (1996) compared effects of cropping systems on soil C over a climate gradient (Potential Evapotranspiration differences=PET) and soil positions within each climate situation. Growing season PET ranged from 1000 mm in the north to 1900 mm in the south. Cropping systems increased in intensity from winter wheat–fallow, to winter wheat–corn (*Zea mays* L.) or sorghum–fallow, to winter wheat–corn or sorghum–proso millet (*Panicum milaceum* L.) or sorghum or forage–fallow, to continuous cropping as soil water levels allow (i.e., opportunity cropping), all with no-tillage. A perennial grass treatment (mixture of cool and warm season types) was included as a reference. Treatments have been in place since 1986.

Cropping system intensification has increased annualized grain production, compared to WF, by 70% in all climatic areas (Peterson et al., 1993). Averaged over all climate areas and soil positions, however, the 3- and 4-year rotations and opportunity (continuous) cropping have increased residue production by only 12%, 25% and 17%, respectively, compared to WF (Table 10 and Fig. 2). On a mass basis this is a residue increase, relative to WF, of about 0.25, 0.5, and 0.3 Mg ha^{-1} annually for the 3-year, 4-year and continuous cropping rotations, respectively. For a 10 year period it is a total increase of 2.5–5 Mg ha^{-1} of residue, which is only about 1.1–2.25 Mg C ha^{-1}.

Table 10
Annualized crop residue production as affected by climate gradient, soil position, and cropping system in eastern Colorado (Mean of 7 years, 1988–1994) (See Peterson and Westfall, 1996)

ET Regime	Soil position	Cropping system			
		W–F [a]	W–C or S–F [b]	W–C or S–M–F [c]	Oppor. [d]
		Mg ha^{-1}			
Low ET [e]	Summit	1.52	2.14	1.97	2.11
	Sideslope	1.78	2.00	2.35	2.34
	Toeslope	1.98	2.82	2.83	2.89
	Mean	1.76	2.32	2.38	2.45
Medium ET [f]	Summit	2.13	2.43	2.58	2.33
	Sideslope	1.96	2.23	2.45	2.31
	Toeslope	3.12	3.94	3.89	3.58
	Mean	2.40	2.87	2.97	2.74
High ET [g]	Summit	1.25	1.34	1.41	1.33
	Sideslope	1.24	1.51	1.74	1.64
	Toeslope	1.39	1.88	2.29	2.05
	Mean	1.45	1.58	1.81	1.67
All site means	Summit	1.66	1.79	2.02	1.92
	Sideslope	1.79	1.91	2.25	2.10
	Toeslope	2.39	2.87	3.01	2.84
	Mean	1.95	2.19	2.43	2.29

[a] W–F=Winter wheat–fallow.
[b] W–C or S–F=Winter wheat–corn or Sorghum–fallow.
[c] W–C or S–M–F=Winter wheat–corn or Sorghum–Proso millet or Forage–fallow.
[d] Oppor.=Continuous cropping.
[e] Low ET=Sterling.
[f] Medium ET=Stratton.
[g] High ET=Walsh.

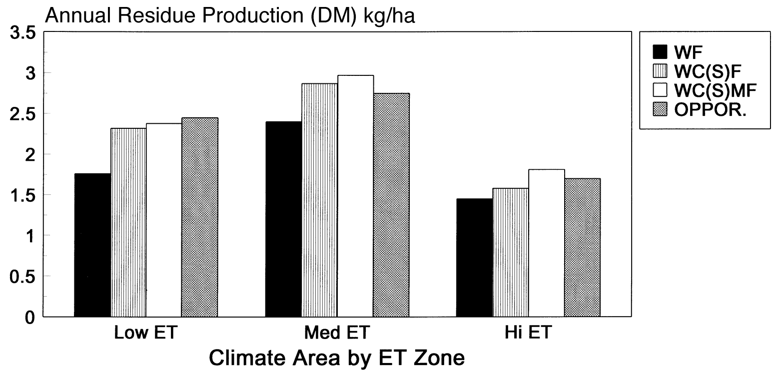

Fig. 2. Annualized residue production in an agroecosystem experiment in eastern CO as affected by climate area and cropping system. See Table 10 for descriptions of climate and cropping system.

Considering, however, that this amount is being placed into the surface 5 cm of soil, which presently contains about 5 Mg ha^{-1}, it represents a significant opportunity for C accumulation in that soil layer. Compared to the total of 20 Mg ha^{-1} of C in the surface 20 cm of soil, this amount is small. Because most of the residue C will be oxidized to CO_2 within a few months, measurable changes in total soil C probably will be slow to occur.

Seeding a soil to perennial grasses increased soil C level by 21% compared to the original 1986 levels (Sherrod et al., 1995) (Table 11). Increasing cropping intensity under no-till management has slowed C losses, but has not stopped them (Fig. 3). All cropping systems, even WF, have maintained or increased the C level of the 0–2.5 cm soil layer (Table 11). The most intensive systems, WC(S)MF and Opportunity cropping, have maintained C levels even in the 2.5–5 cm soil layer. A pictorial summary of soil C changes in Fig. 3 suggests that the most intensive cropping systems may be storing C faster than WF.

One of the puzzling features of the soil C situation is that WCF, which adds 12% more C to the soil annually than does WF (Table 10), has a net soil C loss similar to WF for the 10 year period (Fig. 3). We decided to evaluate the C budget of each system more completely by considering the quantity of C contained in residues on the soil surface. A bulletin published by Peterson et al. (1994) reports the residue amounts present at the end of fallow periods in 1993, the same time at which

Table 11
Soil C in 1986 and in 1993 as affected by cropping system in eastern Colorado. Data averaged over climate areas and soil positions (See Sherrod et al., 1995)

Depth	Cropping system														
	WF [a]			WC(S)F [b]			WC(S)MF [c]			Opportunity [d]			Grass [e]		
	1986	1993	Δ	1986	1993	Δ	1986	1993	Δ	1986	1993	Δ	1986	1993	Δ
cm	kg ha^{-1}														
0–2.5	3280	3270	−10	3240	3210	−30	3170	3410	240	2900	3310	410	3030	4200	1170
2.5–5	2810	2540	−270	2950	2620	−330	2740	2760	20	2700	2600	−100	2740	3720	980
5–10	6140	4890	−1250	6370	5170	−1200	6290	5380	−910	6030	5100	−930	5740	6050	310
0–10	12 230	10 700	−1530	12 560	11 000	−1560	12 200	11 550	−650	11 630	11 010	−620	11 510	13 970	2460

[a] W–F=Winter wheat–fallow.
[b] W–C or S–F=Winter wheat–corn or sorghum–fallow.
[c] W–C or S–M–F=Winter wheat–corn or sorghum–proso millet or forage–fallow; Opportunity=Continuous cropping.
[d] Grass=Mixture of perennial warm and cool season grasses seeded in spring 1986.

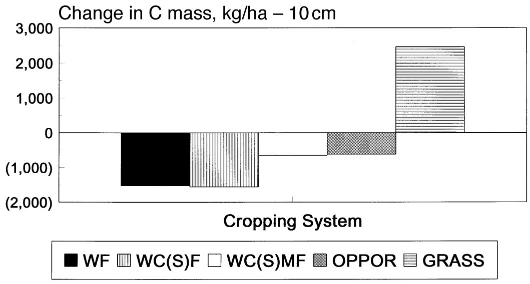

Fig. 3. Change in soil C in an agroecosystem experiment in eastern CO as affected by cropping system after 10 years. See Table 10 for descriptions of climate and cropping system.

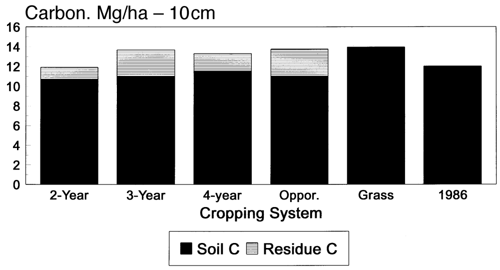

Fig. 5. Soil C and residue C contents in 1993 as affected by cropping system intensification in an agroecosystem experiment in eastern CO (2-, 3-, 4-year systems refer to 1 crop in 2 years, 2 crops in 3 years, etc.).

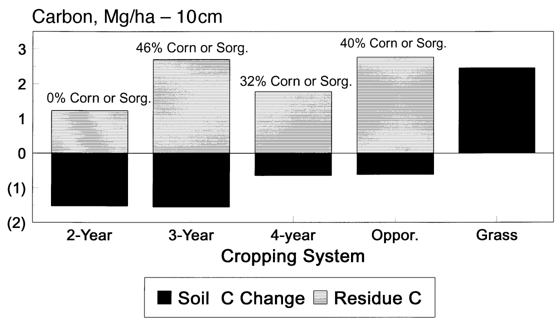

Fig. 4. Change in soil C after 10 years, surface residue C present in 1993, and proportion of the residue returned to the soil that was corn or sorghum stalks as affected by cropping system intensification in an agroecosystem experiment in eastern CO (2-, 3-, 4-year systems refer to 1 crop in 2 years, 2 crops in 3 years, etc.).

soil samples were taken for C analysis. Fig. 4 shows the soil C loss experienced by each system from the initiation until 1993 (solid bars). It also shows the amounts of residue C on the soil surface on the same date (tops of bars). Residue was assumed to be 45% C based on analyses we have conducted in our laboratory. Note that the 3-year, 4-year, and opportunity cropping systems resulted in residue C levels that exceeded the soil C losses (solid bars). Only WF decreased in soil C more than the amount of residue C. The soil under the grass reference treatment increased in soil C from initiation to 1993. No residue C is shown for the grass reference because we harvest the grass annually and there is little residue present. We do acknowledge there is a large C pool in the grass crowns that we have not accounted for in this analysis. Fig. 5 is a summary of the soil C present for each system (summation of soil and residue C) and the data indicate that all systems, except WF, are approaching the grass C levels. All systems, other than WF, have increased in C content relative to the 1986 initial levels.

It appears that the 3-year and opportunity cropping are not adding the C to the soil pool as rapidly as is the 4-year system (Fig. 4). One reason obviously is that the quantity of C added is smaller relative to that for the 4-year system (Table 10). Another contributing factor may be the relative size of the residue pieces. In the 3-year rotation, 46% of the C returned to the soil is in the form of corn or sorghum stalks, which are relatively large pieces compared to wheat or millet residue (Fig. 4). In the 4-year rotation the corn and sorghum represent only 32% of the total C returned, which would allow a more rapid turnover compared to the 3-year rotation. Forty percent of the C returned for opportunity cropping is from corn or sorghum stalks. The difference in residue size, coupled with the quantity, would certainly be a possible explanation for the difference in the systems.

Our conclusion is that on a short-term basis, 10 years or less, the effects of cropping system intensification on soil C should not be investigated independent of residue C still on the surface. How fast the surface C accumulation will be incorporated into the soil organic C pool is not known, but the fact that the 4-year system, the most effective system in terms of C, only has affected the surface 5 cm of soil in a 10 year period means this may be a very long-term proposition. Ortega (1995) also has shown that no-till soils have large amounts of C in residues that are within the surface 2.5 cm of soil, which still are not part of the

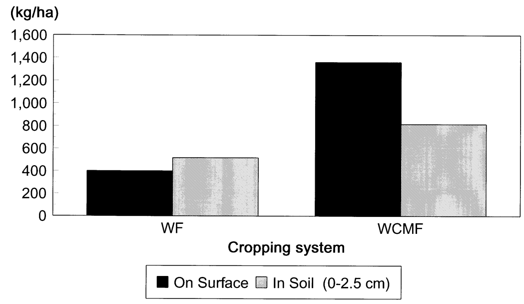

Fig. 6. Carbon present in surface and soil residues (0–2.5 cm) in the wheat–fallow (WF) and wheat–millet–fallow (WCMF) cropping systems in an agroecosystem experiment in eastern CO.

soil organic C pool (Fig. 6). When soils are screened for analysis, this C is removed and not accounted for in either soil or surface residue C.

3. Summary

In the Great Plains, adoption of residue management systems, such as reduced- or no-till systems, coupled with cropping intensification relative to WF, should allow soils to store C in the organic pool. There are many unknowns regarding how rapidly changes will occur, but the data summarized here indicate that changes in the surface 2.5 cm of soil can be detected within 10 years. It is imperative that we continue long-term experiments to evaluate rate of change over an extended period. It is also apparent that we should include residue C, both on the surface of the soil and within the surface 2.5 cm, in our analysis if we are to accurately depict soil C status. The accounting of soil C must be done on a mass basis rather than on a concentration basis.

There are additional experiments in progress, but not discussed in this paper, that may help clarify our understanding of crop rotation and tillage effects on soil C. For example, Deibert and Utter (1989) are studying rotations under plow, fall sweep, fall intertill, and no-till systems in ND. This experiment was started in 1977 on a Fargo clay soil. The rotation under investigation is a row crop alternating with small grains. Organic C analyses are conducted periodically on samples taken from this experiment. Hooker et al. (1982) compared effects of residue removal, addition and burning under irrigated conditions with wheat and grain sorghum at Garden City, KS. This experiment, started in 1970, is on-going and provides an opportunity to evaluate the effects of residue amount on soil C status. This experiment could provide insights regarding residue additions and C. The site is particularly interesting because it is under irrigation and has large C additions relative to dryland situations in the same soil and climatic environments. A complete catalog of long-term experiments would be useful, especially if principle investigators were all collecting the same kinds of measurements. Bulk density for example, is critical to a good analysis, but is often missing. Residue on and in the soil surface also is needed for the best evaluation of soil C status.

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