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Soil Organic Matter Changes in Intensively Cropped Dryland Systems

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ABSTRACT

Continuous cropping or decreasing the frequency of summer fallow (F) in cereal-based dryland rotations may have benefits other than greater water utilization and erosion control. We hypothesized that rotations with no fallow or minimum fallow frequency can produce more biomass and cover than the traditional winter wheat (*Triticum aestivum* L.)–summer fallow systems (W–F), and ultimately, greater amounts of soil organic matter (SOM). To this end, we evaluated changes in various pools of SOM at the 0- to 5- and 0- to 15-cm depths on a Weld loam (fine, smectitic, mesic aridic Paleustolls) that were caused by (i) decreasing fallow or increasing cropping intensities, (ii) specific rotations of the same length but with different crop sequencing, and (iii) accumulated residue and roots from reduced- or no-tillage from 1993 to 1997. Total soil organic carbon (SOC) and N for the 0- to 5-cm depth increased by ≈20% with continuous cropping rotations compared with W–F rotations. Particulate organic matter–carbon (POM–C) doubled, while POM–N, and soluble organic C (OC) increased by one third for the same comparison. At the 0- to 15-cm depth, SOC, POM–C, and POM–N did not differ among systems with fallow, nor among systems with cropping intensities greater than W–F. Thus, significant differences always existed between W–F and continuous cropping. Generally, fallow had a negative influence on SOC accumulation, and continuous cropping a positive influence on surface SOM. Changes in SOC did not correlate with yields in the five-year comparison of this ongoing study.

A MAJOR OBJECTIVE for evaluating rotation and tillage systems is to determine the most efficient and economic crop sequencing for each environment. As government programs for crop subsidies decline or are eliminated, the traditional W–F in the central Great Plains may not be as viable economically and agronomically as are alternative cropping systems that decrease fallow frequency and provide more residue cover against erosion and water loss from evaporation. Besides being more economical, new intensively cropped systems may also slowly increase SOM content, thereby improving the long-term plant environment.

The SOM status correlates well with a number of important soil physical, chemical, and microbiological properties. As SOM increases, soil nutrients such as available N, P, and S, Ca, Mg, K, and micronutrients also increase (Johnson, 1991). Additionally, SOM binds soil particles to form stable aggregates that resist erosion and permit water to infiltrate easily, thereby reducing erosion (Swift, 1991). In adequate quantities, SOM reduces soil crusting and soil bulk density, and helps to maintain a stable soil pH. Overall, SOM improves soil structure and soil tilth, and it provides a favorable medium for crop growth (Rose, 1991).

In recent years, better no-till equipment and cheaper herbicides have made clean tillage operations less necessary. Because of the unfavorable effects of conventional tillage on SOM through erosion and accelerated decomposition (Tiessen et al., 1982; Bowman et al., 1990; Havlin et al., 1990), cropping system research has been directed toward longer rotations and less tillage (Peterson et al., 1997). In the semiarid central Great Plains, this technique is even more important, because greater water storage from less tillage increases the probability of success with the greater cropping intensities (Nielsen et al, 1994).

Previous research in the Great Plains on SOM emphasized different tillage systems (Dick, 1983; Rasmussen and Rohde, 1988; Wagger et al., 1985; Wood et al., 1991), SOM mineralization rates (Wood et al., 1990; Tracy et al., 1990), and fertilization (Campbell and Zentner, 1993; Rasmussen and Rohde, 1988). Very little data exist from studies in which changes in the different pools of SOM have been quantified relative to cropping intensities and rotation length, nor from claims about how these changes may be affecting crop productivity. Bowman and Halvorson (1997) conducted research on cropping intensities as a treatment, but the emphasis was on P distribution.

The objective of this study, therefore, was to evaluate effects of rotations with different cropping intensities and rotation lengths on residue production, SOM, and crop productivity. Three sets of comparisons were made: (i) SOM changes because of increasing cropping intensities, (ii) SOM changes in similar length rotations with different crop sequencing, and (iii) SOM changes from accumulated crop residue amounts for the same treatments (plots) between 1993 and 1997. Selected rotations were also used to evaluate the relationship between soil SOC and grain yield.

MATERIALS AND METHODS

Field plots were established in Washington County near Akron, Colorado, in 1990, on a Weld loam (fine, smectitic, mesic Aridic Paleustolls). Selected physical and chemical properties of the Weld loam sod are given in Table 1 (30-cm

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Abbreviations: CI, cropping intensity; CT, conventional-till; F, summer fallow; NT, no-till; OC, organic carbon; POM–C, particulate organic matter–carbon; RT, reduced-till; SOC, soil organic carbon; SOM, soil organic matter; W–C–F, winter wheat–corn–fallow; W–C–M, winter wheat–corn–proso millet; W–C–M–F, winter wheat–corn–proso millet–fallow; W–C–S–F, winter wheat–corn–sunflower–fallow; W–F, winter wheat–summer fallow; W–M, winter wheat–proso millet; W–M–F, winter wheat–proso millet–fallow.

depth). The research site also contained small inclusions of a Rago silt loam (fine, smectitic, mesic Pachic Argiustolls), and a mixed association, Norka-Colby loam with a poorly developed or absent B horizon (Torriorthents). The area receives an average of 420 mm of annual precipitation with $\approx$80% occurring in April to September. Site elevation is $\approx$1400 m, and open pan evaporation, $\approx$1300 mm.

We used a randomized complete block design with three replications of 60 plots containing 16 different rotations in each replication. Every phase of a rotation was present in a replication. Plot size was 9.1 m by 30.5 m with a 15.2-m alley between each block (Bowman and Halvorson, 1997). While the treatments included three different tillage systems, conventional-till (CT), reduced-till (RT), and no-till (NT), our study was mainly a comparison among longer rotations in minimum- or no-tillage (174 of 180 in minimum- or no-till, and 162 of 180 rotations longer than W–F). The shorter CT W–F was kept as a reference since this practice still predominates in the central Great Plains. The longer rotations were in either RT or NT treatments. The W–F was the only rotation with all tillage comparisons.

Rotation length and cropping intensity were used as treatments. Rotation length is the number of years for the cycle to complete itself. Cropping intensity (CI) is defined as the ratio of crop(s) to crop(s) and fallow in a rotation with each entity assigned a value of one; thus, W–F is 0.5 (1/(1+1)), winter wheat–corn (*Zea mays* L.)–fallow (W–C–F) is 0.67, winter wheat–corn–proso millet (*Panicum miliaceum* L.)–fallow (W–C–M–F) is 0.75, and winter wheat–corn–proso millet (W–C–M) is 1.0. A CI of 1.0 is also referred to as continuous cropping. Thus, while rotation sequences may differ (W–C–F and W–M–F; W–C–M–F and winter wheat–corn–sunflower (*Helianthus annus* L.)–fallow (W–C–S–F)), the cropping intensity may remain the same. Generally, the same CI has similar fertilization, tillage practices, pest control, and biological productivity (Bezdicek and Granalstein, 1989).

Although a discussion of plot management (fertilizer, herbicides, tillage operations), has been given elsewhere (Bowman and Halvorson, 1997), salient points of tillage operations deserve repetition. The no-till system included residual herbicide application (atrazine [2-chloro-4-ethylamino-6-isopropylamino-s-triazine], and clomazone [2-(2-chlorophenyl)methyl-4, 4-dimethyl-3-isoxazolidinone]) after wheat harvest, and contact or burn-down herbicide in the following spring for weed escapes. Reduced-tillage was a combination of residual herbicides after harvest and two-sweep tillage operations with minimal soil disturbance. Conventional tillage mixed the top 5 to 10 cm five times using both a sweep plow, and sweep plow with a mulch treader, during the 14-mo fallow period.

All soil samples for organic matter comparisons were determined on the 0- to 5- and 0- to 15-cm depths in the spring of 1993 and 1997. The following analyses were determined on all soils: Bulk density was determined by the core method at the 0- to 5- and 0- to 15-cm depths (Blake and Hartge, 1986) for volumetric content adjustments. Soil pH (McLean, 1982) and texture (Gee and Bauder, 1986) were determined from established methods. SOC and N and POM–C and N were determined with a C–N auto analyzer and by chromic acid (Heanes, 1984) and Kjeldahl digestions (Nelson and Sommers, 1982).

Particulate Organic Matter Determination

Particulate organic matter was determined essentially from the method of Gregorich and Ellert (1993). Ten grams of soil was used instead of 25. Samples were placed on top of a 0.053-mm screen, and clay and silt were washed with water through the screen until water ran clear. The rest of the fines (and sand and POM) were then quantitatively transferred to a 250-mL Erlenmeyer flask with about 50 to 100 mL water, to which 0.5 to 0.7 g of sodium hexametaphosphate was added. Samples were shaken for 2 h, after which time the rest of the fines were removed through the 0.053-mm screen by washing again until water ran clear. The sand and POM retained on the screen were then quantitatively transferred to a beaker with as little water as possible, and the remaining water was evaporated overnight at 60°C. The net weight of sand and POM was determined. Material (sand and POM) was finely ground with a mortar and pestle for determination of SOC and N.

Table 1. Selected soil physical and chemical properties of Weld loam at the 0–15 cm depth in 1993.

Soil parameters	Native sod	Cultivated site
pH (water)	6.2	5.8
Sand (g kg^{-1})	38	40
Silt (g kg^{-1})	35	35
Clay (g kg^{-1})	27	25
BD (Mg m^{-3})	1.20	1.35
CEC (cmol kg^{-1})	14	11
Total P (mg kg^{-1})	570	545
CaCO$_3$ (g kg^{-1})	0	0

Soluble Organic Carbon Determination

Soluble organic C was determined by shaking 5 g soil for 30 min with 25 mL of 0.5 *M* NaHCO$_3$ solution (pH = 8.0). Note that this solution is not the same as the Olsen-P extracting solution, which has a pH of 8.5 because of added NaOH. After filtering, a 10-mL aliquot was obtained and concentrated to dryness at 60°C overnight in a 100-mL beaker. The resultant organic C in the sample was determined colorimetrically by chromic acid reduction (Heanes, 1984; Bowman, 1998). Glucose–C samples were treated similarly to ascertain that OC was not lost during the overnight drying. After wet digestion of C, digest was quantitatively transferred with distilled water to a 50-mL graduated test tube and contents made to a total of 25-mL volume with water before reading at 625 nM against glucose–C.

Statistical Analysis of Data

Plot treatments used in comparisons among CI, rotation length, and time are given in Table 2. A preliminary examination of results showed that no significant difference in SOM content existed between RT and NT treatments for the 15 matched comparisons (e.g., W–C–F, NT vs. W–C–F, RT; W–F, NT vs. W–F, RT). Bauer and Black (1981) found similar results. Comparisons for CI were made with five smaller blocks (closely clustered samples) with each block containing two replications of each cropping intensity (40 samples: 5 blocks × 2 replications × 4 CI). Only the Weld loam soil series was used in this blocking. Specific rotations (all three replications) of the same length were also selected for comparisons (e.g., W–F vs. W–M; W–C–F vs. W–C–M). Lastly, we evaluated the effects of time on SOM changes with the same treatments or rotations (for example, W–C–F in 1993 vs. the same plot in 1997).

Analysis of variance for multiple comparisons was determined for significance ($P = 0.10$) by Duncan's LSD mean comparisons. The random variation (error mean square) in the cropping intensity study where selected treatments were used was compared to the random variations in the 2-yr and 3-yr rotations in the randomized block design for sameness. A *t*-test ($P = 0.05$) was used for the 1993 vs. 1997 data comparison. A linear regression analysis was determined for annualized grain yield (e.g., wheat grain yield plus corn grain yield divided by three for W–C–F) vs. soil organic C concentration in the 0- to 5-cm depth.

Table 2. Experimental design with main effects and relevant plot treatments.

Main effects	Treatments	n†
CI 0.50	W–F‡ (CT)§; W–F (RT)§; W–F (NT)§	10
0.67	W–C–F (RT); W–M–F (RT); W–S–F (RT)	10
0.75	W–C–M–F (RT); W–C–S–F (RT); W–M–S–F (RT)	10
1.00	W–M (NT); W–C–M (NT); M–S (RT)	10
Rotation 2-y	W–F (RT and NT); W–M (NT)	18
3-y	W–C–F (RT); W–M–F (RT); W–C–M (NT)	27
Time 1993	Rotations with fallow	40
1997	Rotations without fallow	15
Rotations for SOC vs. grain yield	W–F, W–C–F, W–M–F, W–C–M–F, W–M, W–C–M	24

† n is number of treatments (plots) used.
‡ M–S, proso millet-sunflower; W–C–F, winter wheat-corn-fallow; W–C–M, winter wheat-corn-proso millet; W–C–M–F, winter wheat-corn-proso millet-fallow; W–C–S–F, winter wheat-corn-sunflower-fallow; W–F, winter wheat-summer fallow; W–M, winter wheat-proso millet; W–M–F, winter wheat-proso millet-fallow; W–M–S–F, winter wheat-proso millet-sunflower-fallow; W–S–F, winter wheat-sunflower-fallow.
§ CT = conventional till; RT = reduced till; NT = no-till.

RESULTS AND DISCUSSION

The native sod and the cultivated site (composited value) differed primarily in pH and bulk density (Table 1). Total soil P also differed significantly, primarily because of the significantly higher organic P content in the sod. Generally, for both soils the depth of the A horizon was ≈20 cm with free calcium carbonate appearing around the 50-cm depth.

The selective partitioning of the experiment with respect to blocking of cropping intensities and the statistical results were deemed valid for the following reasons. Firstly, no significant difference for SOM existed between reduced- and no-till treatments. Thus, comparisons of similar cropping intensities, which usually produce similar biomass over the long term, can be made directly without the confounding from tillage. Secondly, an assessment of the variability in the error mean square for the cropping intensity study vs. the rotation study showed no significant differences. As a matter of fact, a greater variability existed for the cropping intensity treatments than for the rotation treatments. Thirdly, blocks were significantly different in SOC content, which suggests that each cropping intensity in the five blocks sampled a part of the variability inherent in the whole field.

Cropping Intensity Study

The results for SOC and N content for the 0- to 5-cm depth, as CI increased from 0.5 to 1.0, showed two different pool sizes for SOC and three different pool sizes for total N (Table 3). For SOC, no difference existed among rotations with a fallow period. Our CI of 1.0 (continuous cropping) averaged ≈20% greater SOC than the 0.5 and the 0.67 intensities. Although results for the CI of 0.75 showed a greater mean content than the CI of 0.5 and 0.67, data differences were not significant. Results of Wood et al. (1991), who worked with similar soils, showed an increase in SOC in W–C–M–F relative to W–F treatment. Their treatments, however, did not include continuous cropping. Results for total N showed no difference for CI of 0.67 and 0.75, but the 0.5 treatment (W–F) was significantly lower, and the 1.0 treatment (continuous cropping) was significantly greater than the two intermediate treatments. Carbon to nitrogen ratios varied from 9.2 to 9.6. The N pool did not include nitrates, so it reflected a ratio of organic C to organic N.

The POM–C is usually regarded as a pool of intermediate decomposition and as a sensitive indicator of soil management (Elliott et al., 1994). The data for the POM–C, which usually reflect the amount of residue, litter, and shallow roots (0–5 cm), increased with greater CI. The CI of 1.0 had the highest POM–C content, and the CI of 0.5, the lowest. Particulate organic matter–C content in the other two cropping intensities were intermediate. The POM–C content for the CI of 1.0 was nearly double that of the POM–C in the 0.5 treatment. We attributed this to greater plant biomass production in systems that produced more litter and roots for POM–C accumulation. The data showed that about half the total SOC was derived from the POM–C for the treatments without fallow, and ≈40% for treatments with fallow. These percentages are higher than those obtained by Cambardella and Elliott (1992), who showed 25% POM–C for no-tillage, but they are more

Table 3. Selected soil organic matter properties as a function of cropping intensity at the 0–5 and 0–15 cm depths.

Cropping† intensity	Soil depth	Soil OC§	Total N	POM‡ C	POM N	Soluble OC
	cm	Mg ha^{-1}				
0.50	0–5	6.1b	0.63c	2.10c	0.20b	0.40b
0.67	–	6.2b	0.67bc	2.70b	0.20b	0.39b
0.75	–	6.6b	0.72b	2.90b	0.17b	0.44b
1.00	–	7.7a	0.79a	4.20a	0.26a	0.55a
0.50	0–15	15.0b	1.46a	3.80b	0.32b	0.88c
0.67	–	15.8ab	1.48a	4.20ab	0.40ab	0.97bc
0.75	–	15.8ab	1.50a	4.60ab	0.44ab	1.050b
1.00	–	17.0a	1.58a	5.00a	0.50a	1.190a

† Cropping intensity is the ratio of crop(s) to crop(s) and fallow in a rotation (0.5 is wheat–fallow and 1.0 is continuous cropping).
‡ POM is particulate organic matter.
§ OC is organic carbon.

in line with the data of Franzluebbers and Arshad (1997), who showed about 45%. The use of continuous cropping and less tillage and a much smaller depth in our studies (5 vs. 20 cm) may account for some of these differences with Cambardella and Elliott (1992).

Data for the POM–N and soluble OC content at 0 to 5 cm were similar to the data for the SOC at the same depth. Results for the CI of 1.0 were significantly greater (≈30 to 40%) than results for all other CI treatments. While the SOC/N ratio in the whole soil approximated 10, that of the POM–C /POM–N varied widely with the greater cropping intensities (0.75, 1.0) having much wider C/N ratios. The soluble OC as measured by extraction with bicarbonate represented ≈6% of the total SOC. The soluble OC pool is important because it may improve the stability of aggregates (DeLuca and Keeney, 1993) and increase water infiltration (Beare et al., 1994), compared to a conventional W–F system.

Data for the 0- to 15-cm depth showed two different pool sizes for the SOC content. No difference among CI treatments of 0.5 to 0.75 existed, nor among CI of 0.67 to 1.0. Thus, the only significant difference existed between CI of 0.5 (W–F) and 1.0 (continuous cropping). This was not unexpected since continuous cropping treatments like W–C–M usually produce ≈50% more biomass than W–F treatments (Anderson, 1997). It is quite likely though, that with time, the intermediate cropping intensities (0.67, 0.75) may become significantly different from the 0.5 and the 1.0.

No difference in total N at 0 to 15 cm existed, but POM–C and POM–N contents showed the same trend as those for the SOC where CI of 1.0 differed significantly from 0.5 only.

The soluble OC showed three different pool sizes at the 0- to 15-cm depth. Rotations with CI of 0.5 and 0.67 were the same, those of 0.67 and 0.75 were the same, but the CI of 1.0 (continuous cropping system) was significantly greater than all the others. The soluble OC for continuous cropping was ≈35% greater than soluble OC in W–F systems. Crop residues (tops and roots from continuous cropping in various stages of decomposition) could have provided the necessary soil binding materials (polysaccharides and fungal hyphae) for a more long-term productive system (Elliott and Coleman, 1988; Beare et al., 1994).

Rotations Study

The rotation study was a randomized complete block design. Soil organic matter comparisons were made on selected 2-yr and 3-yr rotations (Table 4). These were specific rotation comparisons without blocking where all three replication and all phases of the rotation were used. For both the 2-yr rotations (six samples of each rotation) and the 3-yr rotations (nine samples of each), no difference in SOC and total N were found at the 0- to 15-cm depths. The W–M and W–C–M continuous cropping treatments, however, were both higher in SOC contents at the 0- to 5-cm depths than the comparable plots with fallow. These results were consistent with those shown earlier for the cropping intensity study.

Table 4. Selected soil organic matter properties as a function of specific rotations at the 0–5 and 0–15 cm depths.

Rotation length	Crop sequence	0–5 cm		0–15 cm	
		SOC†	Total N	SOC	Total N
Year		Mg ha^{-1}			
2	W–F‡ (RT)§	6.0b	0.80b	15.6a	1.46a
	W–F (NT)§	5.8b	0.81b	16.2a	1.48a
	W–M (NT)	7.3a	0.88a	16.8a	1.52a
3	W–C–F‡ (RT)	5.9b	0.58b	14.8a	1.48a
	W–M–F‡ (RT)	5.7b	0.58b	14.6a	1.48a
	W–C–M (NT)	7.0a	0.67a	15.4a	1.54a

† SOC is soil organic carbon.

‡ W–C–F, winter wheat-corn-fallow; W–C–M, winter wheat-corn-proso millet; W–F, winter wheat-summer fallow; W–M–F, winter wheat-proso millet-fallow.

§ RT is reduced till; NT is no-till.

Changes in Soil Organic Matter from 1993 to 1997

A true evaluation of gains or losses in SOM can best be done by assessing changes in time for the same plot (assuming enough time has gone by for such changes to occur). This approach removes the necessity to assume sameness among all cropping intensities when the experiment is begun. It can also test true positive changes in SOM as opposed to positive differences, which may be due to the reduction in rate of loss from two or more different treatments. In the case of the latter, the treatment losing less C shows a net increase over another treatment losing more C.

Changes in SOC between 1993 and 1997 were compared on selected plots with fallow and without fallow (Table 5). Although not shown in the data, soil OC tended to increase as fallow period decreased, but differences among treatments with fallow were not significant. With continuous cropping treatments, however, SOC was ≈10% higher at the 0- to 5-cm depth after 4 yr. Differences within the 0- to 15-cm depth were not significant. The surface accumulation of crop residue and SOM, however, is crucial for erosion control and greater water-use efficiency (Peterson et al., 1996). More time may be necessary to express differences at greater depths.

Yield Correlations with Soil Organic Matter

The importance of increased SOM is its effect in improving soil physical properties, conserving water, and increasing available nutrients. This should ultimately lead to greater biomass and yield production. However,

Table 5. Changes in soil organic carbon in crop rotations with and without fallow (1993 vs. 1997).

Treatment	0–5 cm		0–15 cm	
	1993	1997	1993	1997
	Mg ha^{-1}			
Plots with fallow				
Soil organic carbon	5.8	6.1	14.7	15.4
Total N	0.54	0.61	1.42	1.42
Plots without fallow				
Soil organic carbon	6.5	7.2*	15.4	16.6*
Total N	0.61	0.74	1.42	1.62

* $P = 0.05$ for matched comparisons between dates.

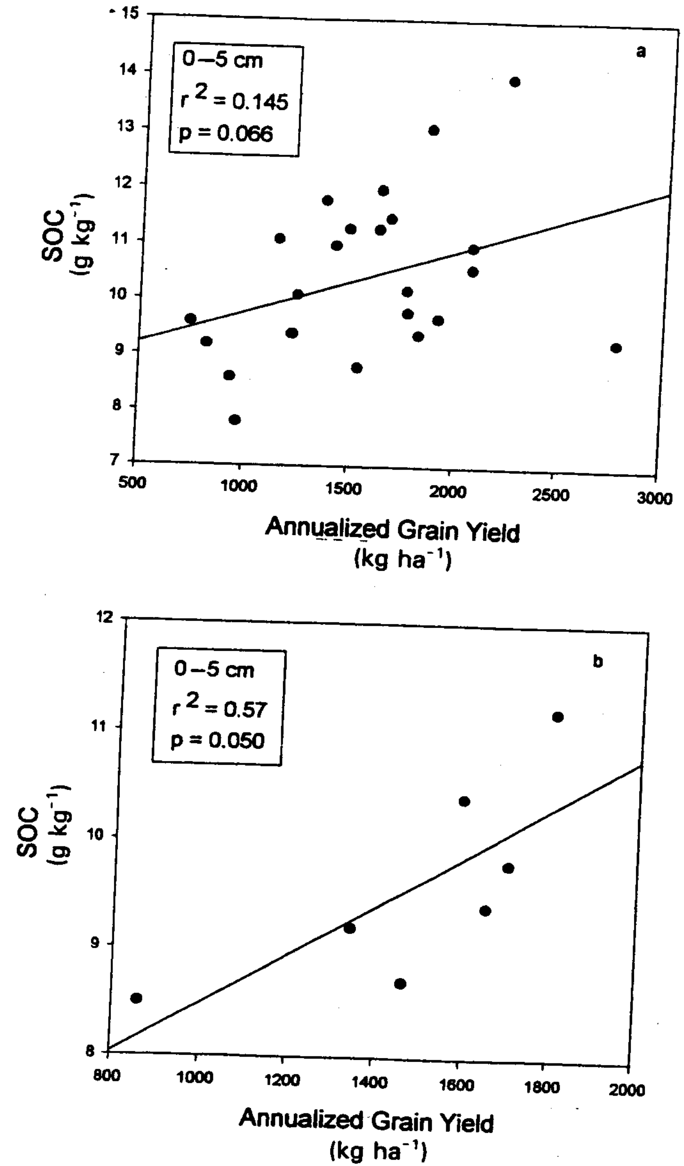

Fig. 1. Linear regression analysis for annualized grain yields and SOC concentration at the 0–5 cm depth: (a) selected rotations; (b) composited grain yields and SOC concentrations.

linear regression analysis (Fig. 1) showed no significant difference between annualized crop yield and SOC concentrations at 0 to 5 cm when a large number of treatments ($n = 24$) were used. When treatments were composited (e.g., one yield value and one SOC concentration value for all nine W–C–M plots), a significant positive response was shown, but with a coefficient of determination of 0.57. Quite likely, soil spatial variability and its effects on water use and fertility were greater influences on yield at this time. Also, SOC concentration is more a function of residue and roots (Havlin et al., 1990) remaining after harvest since, at times, little or virtually no yield is obtained (of corn in very dry years, or of corn after sunflower has dried out the soil profile), yet leaf and stem biomass and residue are produced.

CONCLUSIONS

While the majority of studies on SOM loss and concomitant decrease in fertility have been directed towards comparison of conventional-till with reduced- and no-till systems in fallow, our study showed the importance of continuous cropping to increase SOM content in mostly-no-tillage systems. Any inclusion of fallow had a negative influence on SOC in the central Great Plains. Our generally moist, warm late spring and early summer periods during fallow probably created ideal conditions to decompose SOM. The data did show, however, that continuous cropping systems can increase cover (POM–C) relative to the conventional W–F. Increased cover and crop residue will reduce erosion and increase SOM and nutrient cycling, and ultimately, create a more favorable plant growth environment.

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