Cropping System and Nitrogen Effects on Mollisol Organic Carbon

C. A. Robinson,* R. M. Cruse, and M. Ghaffarzadeh

ABSTRACT

Time, fertilizer, tillage, and cropping systems may alter soil organic carbon (SOC) levels. Our objective was to determine the effect of long-term cropping systems and fertility treatments on SOC. Five rotations and two N fertility levels at three Iowa sites (Kanawha, Nashua, and Sutherland) maintained for 12 to 36 yr were evaluated. A 75-yr continuous corn (*Zea mays* L.) site (Ames) with a 40-yr N-P-K rate study also was evaluated. Soils were Typic and Aquic Hapludolls and Typic Haplaquolls. Four-year rotations consisting of corn, oat (*Avena sativa* L.), and meadow (alfalfa [*Medicago sativa* L.], or alfalfa and red clover [*Trifolium pratense* L.]) had the highest SOC (Kanawha, 32.1 g/kg; Nashua, 21.9 g/kg; Sutherland, 27.9 g/kg). Corn silage treatments (Nashua, ≤18.9 g/kg; Sutherland, ≤23.2 g/kg) and no-fertilizer treatments (Kanawha, 25.3 g/kg; Nashua, ≤20.9 g/kg; Sutherland, ≤23.5 g/kg) had the lowest SOC. A corn-oat-meadow-meadow rotation maintained initial SOC (27.9 g/kg) after 34 yr at Sutherland. Continuous corn resulted in loss of 30% of SOC during 35 yr of manure and lime treatments. SOC increased 22% when N-P-K treatments were imposed. Fertilizer N, initial SOC levels, and previous management affected current SOC levels. Residue additions were linearly related to SOC (Ames, r^2 = 0.40; Nashua, r^2 = 0.82; Sutherland, r^2 = 0.89). All systems had 22 to 49% less SOC than adjacent fence rows. Changing cropping systems to those that conserve SOC could sequester as much as 30% of C released since cropping began, thereby increasing SOC.

The atmospheric CO_2 concentration has gained much attention for its potential contribution to global warming. Agriculture affects atmospheric CO_2 concentrations through consumption of fossil fuels, clearing of forested lands for food production (U.S. Congress, 1991; Wallace et al., 1990), and alteration of SOC levels by agricultural management practices. Agricultural fuel consumption and N fertilizer production release 35.4 Tg C yr^{-1} into the atmosphere. Based on current production practices, the Council for Agricultural Science and Technology (1992) estimates another 2.7 Tg C yr^{-1} are released into the atmosphere from cultivated soils in the USA alone.

Changes in SOC can be attributed to crop species grown, cropping systems (including rotations), residue management practices, fertilizer applications, tillage practices, and other management factors (Havlin et al., 1990; Unger, 1968). Anderson et al. (1990), Bauer and Black (1981), and Havlin et al. (1990) independently showed that SOC losses were directly related to tillage intensity. Manure applications modified the tillage–SOC relation, increasing SOC even with high-intensity conventional tillage (Anderson et al., 1990). Crop rotations may retard SOC losses relative to those observed in continuous corn systems (Odell et al., 1984). Rasmussen and Rohde (1988) reported linear increases in SOC with applied N fertilizer, and noted that crop residue has a positive impact on SOC. Rasmussen and Parton (1994) reported that the rate of SOC change was directly related to C input from crop residues and amendments.

Mann (1986) reported that SOC losses from a number of cultivated soils averaged <20% of initial levels, and that quantity and direction of change were related to initial SOC. Mann (1986) noted the greatest change in the first 20 yr. Lucas et al. (1977) suggested that more than 60 yr were required to approach new steady-state conditions on Michigan soils. Changes in SOC quantity following implementation of a new management practice, and the time required to achieve new SOC equilibria, will be ecosystem dependent because climate, parent materials, topography, biotic factors, and time affect soil equilibria (Jenny, 1941).

The recent conversion of cropland to perennial grass cover through the Conservation Reserve Program increased SOC in the Great Plains and potentially sequestered C (Gebhart et al., 1994). Kern and Johnson (1993) suggested that increasing conservation tillage to 76% of planted cropland would change agricultural systems from C sources to C sinks. A concomitant conversion to cropping systems that conserve, or increase, SOC could also help move agriculture from C source to C sink. The impact of long-term soil and crop management on SOC, and subsequently on sustainability of the soil resource, is not clear. The objective of this study was to determine the effects of several Iowa long-term cropping systems and fertilizer applications on SOC of Typic Haplaquolls and Typic Hapludolls.

METHODS AND MATERIALS

Cropping Systems Studies

Several long-term rotation–fertility studies exist in Iowa. Three sites were chosen for study: North Central Research Center at Kanawha, Northwest Research Center at Sutherland, and Northeast Research Center at Nashua. The study at Kanawha was established in 1954 on a Webster clay loam (fine-loamy, mixed, mesic Typic Haplaquoll), with a mean particle-size distribution of 21.9% sand, 44.9% silt, and 33.2% clay. The study at Sutherland was established in 1956 on a Galva silty clay loam (fine-silty, mixed, mesic Typic Hapludoll), with a mean particle-size distribution of 2.6% sand, 62.2% silt, and 35.2% clay. The study at Nashua was established in 1979 on Kenyon (fine-loamy, mixed, mesic Typic Hapludoll) and Readlyn (fine-loamy, mixed, mesic Aquic Hapludoll) loams, with a mean particle-size distribution of 31.9% sand, 45.6% silt, and 22.4% clay. Mean annual precipitation is 813 mm at Kanawha, 711 mm at Sutherland, and 825 mm at Nashua.

The experimental design at Kanawha and Sutherland was a split-split plot design, replicated twice with crop year (first, second, third, or fourth year of rotation) as the main plot, crop rotation (corn, corn–soybean [*Glycine max* (L.) Merr.], corn–corn–oat–meadow, etc.) as the subplot, and N fertilizer

C.A. Robinson, Div. of Agriculture, West Texas A&M Univ., WTAMU Box 998, Canyon, TX 79016; and R.M. Cruse and M. Ghaffarzadeh, Dep. of Agronomy, Agronomy Hall, Iowa State Univ., Ames, IA 50011. Iowa State Univ. Journal Paper no. J-15950 of the Iowa Agriculture and Home Economics Exp. Stn. Project no. 2556. Received 29 Aug. 1994. *Corresponding author (car@wtamu.edu).

Published in Soil Sci. Soc. Am. J. 60:264-269 (1996).

rates as sub-subplots (6.1 m by 12.2 m, 74.3 m^2). The experimental design at Nashua was a split plot design, replicated three times, with rotation–crop year as the main plot and N rate as the subplot (4.6 m by 15.2 m, 69.7 m^2).

All crop rotations and N rates in the rotation–fertility studies were not used. Table 1 lists the crop rotations and fertility levels selected for study by location. The N rates chosen were consistent since initiation within each location. Fertilizer N rates were not consistent across locations as N recommendations vary with soils and climate. Conventional tillage systems were used, but varied with location. In the late 1970s, chisel and field cultivating operations replaced some moldboard operations. Soybean and corn were cultivated once or twice after emergence and before canopy closure. Meadow was alfalfa or a mixture of alfalfa and red clover. Meadow crops were interseeded with oat and received no subsequent tillage until the meadow crop was plowed. Oat straw was baled. The meadow was cut and baled two or three times annually. All bales were removed. Corn harvested for silage was removed from the plots, leaving 7 to 15 cm of stubble. Stalks and stubble remained in corn plots harvested for grain. Only seeds were removed from soybean plots. Herbicide treatments were used to control weeds and to kill the meadow before moldboard plowing.

Fence-row samples were taken for comparison with a noncropped soil. There was no statistical difference in the texture of fence-row samples and the texture of rotation–fertility samples at any location. There was no noticeable soil deposition in the fence rows at Sutherland and Kanawha. These fences were between adjacent fields, within 15 m of the rotation–fertility plots. The minimum width of grass strips associated with the fence rows at all locations was 15 m. The grass strips were used as roads between experiments. Samples were taken from nontrafficked areas. There was no noticeable soil deposition at Nashua though the fence was near a road. This was the nearest fence row on a similar soil series though it was 300 m from the rotation–fertility plots. The primary species in all fence rows was smooth bromegrass (*Bromus inermis* Leyss.). All fences were in place at the initiation of the experiments.

Five samples per plot were composited from the 0- to 15-cm depth for SOC analysis. Samples taken in 1957 (year of initiation) were available for the Sutherland site. No information was available on sampling methodology or number of samples composited. The Walkley–Black method (Nelson and Sommers, 1982) was used for SOC determination. One surface core sample (75-mm i.d., 75-mm length) was taken for bulk density per plot from the center row, near the center of the plots five times during the 2 yr. Mean bulk density was used to determine mass of SOC.

Statistical analysis of the cropping systems first determined the effect of crop year within rotation (i.e., corn year in corn–soybean) on SOC levels at each location. Orthogonal contrasts revealed no significant differences in SOC due to crop year within the rotation. Therefore, all data for each rotation were pooled (resulting in eight replications per cropping system at Sutherland and Kanawha, and three replications for corn, six replications for corn–soybean, and 12 replications for corn–corn–oat–meadow at Nashua) and analyzed for differences due to rotation. Individual locations were analyzed using actual SOC. Relative SOC was calculated by dividing actual SOC by the fence-row SOC at each site. Relative SOC was used in a combined analysis that examined the cropping systems common to all locations. All statistical analyses used the SAS package (SAS Institute, 1989). Specific, one-degree-of-freedom contrasts were used to determine differences among cropping systems. A 0.05 significance level was used for all analyses.

Table 1. Locations and treatments selected for study.

Crop rotation	N rates†
	kg ha^{-1} yr^{-1}
North Central Research Center, Kanawha, IA	
Continuous corn, grain, 0N	0
Continuous corn, grain, N	180
Corn-soybean-corn-soybean	180
Corn-corn-oat-meadow	180
Corn-oat-meadow-meadow	180
Fence row for comparison	0
Northeast Research Center, Nashua, IA	
Continuous corn, grain, 0N	0
Continuous corn, grain, N	180
Continuous corn, silage, 0N	0
Continuous corn, silage, N	180
Corn-soybean	180
Corn-corn-oat-meadow	180
Fence row for comparison	0
Northwest Research Center, Sutherland, IA	
Continuous corn, grain, 0N	0
Continuous corn, grain, N	200
Continuous corn, silage, 0N	0
Continuous corn, silage, N	200
Corn-soybean-corn-soybean	200
Corn-corn-oat-meadow	135
Corn-oat-meadow-meadow	135
Fence row for comparison	0

† Nitrogen applied to corn plots only; P and K applied as needed.

Continuous Corn Fertility Study

A continuous corn experiment was established at the Agronomy Farm near Ames in 1915 on Nicollet (fine-loamy, mixed, mesic Aquic Hapludoll) and Clarion loams (fine-loamy, mixed, mesic Typic Hapludoll) with a mean annual precipitation of 812 mm. From 1915 to 1951, the experiment had four treatments with no replication: manure, lime, manure + lime, and no amendments (checks). The manure rate was 4.5 Mg ha^{-1} yr^{-1}, and lime was added as needed to neutralize acidity. These plots were 8.5 by 51.2 m (437 m^2). In 1952, a N-P-K fertilizer rate study was established on the original study area with four N rates (0, 45, 90, and 180 kg/ha) and two P-K rates (0 and 67 kg/ha). Each of the former manure–lime test plots constituted one replication of the fertilizer rate study. The eight N and P-K combinations were randomly located on each of the former plots, resulting in four replications. The Clarion loam was excluded from the N-P-K study. The N-P-K plot sizes were 8.5 by 6.4 m (54.6 m^2). The 45 kg N/ha rate was changed to 270 kg N/ha in 1977, and was excluded from the 1992 evaluation. Other cultural practices included conventional tillage and herbicide treatments. Plots were sampled for SOC in 1917, 1936, 1952, 1958, and 1992. Samples in 1992 were composites of six 25-mm-diam. cores per plot to a 15-cm depth.

The Leco CHN-800 (Leco Corp., St. Joseph, MI) was used to determine SOC (Tabatabai and Bremner, 1991) in the 1992 continuous corn-fertility study. Previous total C determinations used a dry combustion technique (Salter, 1916; Winters and Smith, 1929). The Leco and dry combustion methods used the same temperature of combustion and a stream of O_2. Winters and Smith (1929) used 1 to 2 g, an oxidizing agent with the soil, and a 10-min combustion time, whereas the Leco method used 0.15- to 0.35-g samples and a 4-min combustion time. Comparisons of combustion methods revealed good agreement in reported C values (r^2 = 0.999) (Soon and Abboud, 1991; Yeomans and Bremner, 1991).

Covariate analysis determined the effect of 1952 SOC on subsequent SOC at the 0.05 significance level. Relative SOC was calculated based on the 1917 SOC for the manure-lime study and for the N-P-K rate study.

Residue additions to continuous corn plots were estimated from yield data using a conversion factor of 1.5 kg residue/kg grain harvested (Donald and Hamblin, 1976). Residue additions to silage plots were estimated at 5% of harvest weight (after Lucas et al., 1977). Plot yield data were not available, so average yield per treatment was used. A multiple regression analysis was conducted to test whether residue additions, fertilizer treatments, and initial SOC significantly affected current SOC at the 0.05 significance level. Regression analysis determined relations between annual residue additions under continuous corn (grain and silage, with N rates) and SOC at Ames, Nashua, and Sutherland.

Soil organic C data, in combination with surface bulk density, were used to estimate the SOC of surface soil (0-15 cm) at Kanawha, Nashua, and Sutherland. Estimates were developed for three uses: row crops (corn, corn-soybean), 4-yr rotations, and native grassland (represented by fence-row samples).

RESULTS AND DISCUSSION

Cropping Systems Studies

Soils differed in their response to management practices. Location significantly affected SOC relative to fence-row SOC (Table 2). It was assumed that fence-row SOC was indicative of initial SOC. Sutherland had the greatest relative SOC (0.70) while Nashua had the lowest (0.57) and Kanawha was intermediate (0.63) (Table 3). Soils at Nashua were the most susceptible to loss of SOC from the cropping and tillage systems involved, whereas the soils at Sutherland were the least susceptible. It was probable that the finer textured soils at Sutherland physically stabilized SOC against exposure and decomposition (Voroney et al., 1981). Soils at Kanawha had a higher clay content than those at Nashua, and probably also were physically stabilized, though to a lesser extent than those at Sutherland.

Cropping system significantly affected SOC at all locations (Table 2). Differences existed among the cropping systems means at Kanawha and Sutherland, but differences among means at Nashua were not well defined (Table 3). The difference in responses among locations were attributed to the duration of the experiments. Rotations had been ongoing at Kanawha for 36 yr, Sutherland for 34 yr, and Nashua for 12 yr. The Nashua experiment had completed three full cycles of the 4-yr crop rotations, whereas the other sites had completed 8.5 to 9. It is expected that in another 10 to 30 yr, differences in SOC among cropping system means at Nashua will become more evident, as at the other locations. Kanawha and Sutherland SOC may not reflect steady-state levels. Lucas et al. (1977) suggested that 60 or more years of continuous management may be required for such conditions to develop.

Cropping systems ranked in decreasing order of SOC were 4-yr rotations, continuous grain corn, corn-soybean, and continuous silage corn. The unfertilized treatments had significantly less SOC than their fertilized counterparts. Relative SOC was 0.69 in corn-corn-oat-meadow, 0.64 in fertilized continuous grain corn, 0.59 in unfertilized continuous grain corn, and 0.61 in corn-soybean (Table 3). These results agreed, in part, with those of Hageman and Shrader (1979), who found that organic matter content of a Typic Haplaquoll was affected more by crop rotation than by N fertilizer additions. Examination of the SOC means in fertilized and unfertilized silage and grain corn at Kanawha and Sutherland revealed that N fertilizer additions significantly affected SOC within cropping systems (Table 3). However, it appeared the cropping system determined the general SOC level, as SOC in silage was less than that in grain corn. The SOC decreased for all systems except corn-oat-meadow-meadow after 34 yr of cropping at Sutherland. The SOC levels in the 4-yr rotations were greater than in the other cropping systems and were not significantly different from one another. Thus, rotations were more effective at conserving SOC than the other cropping systems. This agreed with the results of Odell et al. (1984), who found that crop rotations retarded the loss of SOC relative to continuous corn on an Aquic Argiudoll in Illinois. Odell et al. (1984) further stated that appropriately fertilized crop rotations produced the greatest crop yields and maintained SOC at the highest level.

Table 2. Probability of larger *F* values from the analysis of variance for relative and actual soil organic carbon (SOC).

Variance source	*F* value	*P* > *F*
Relative SOC		
Location	25.99	0.0011
Cropping system	8.59	0.0137
Contrasts		
Locations		
Kanawha vs. Nashua	12.01	0.0134
Sutherland vs. Kanawha, Nashua	39.98	0.0007
Cropping systems		
Corn-corn-oat-meadow vs. others	19.48	0.0045
Actual SOC		
North Central Research Center, Kanawha, IA		
Cropping system	15.92	0.0047
Northeast Research Center, Nashua, IA		
Cropping system	4.18	0.0196
Northwest Research Center, Sutherland, IA		
Cropping system	33.53	0.0001

Table 3. Soil organic carbon (SOC) by location and cropping system.

	Location			
			Sutherland	
Cropping system†	Kanawha	Nashua	Current	Initial‡
	SOC, g/kg			
Silage, 0N	–	18.5c§	21.5d	27.5
Silage, N	–	18.9bc	23.2c	27.2
Corn, 0N	25.3c	20.9abc	23.5c	28.8
Corn, N	29.4b	21.1ab	25.7b	28.6
CSb	28.2b	19.7bc	23.7c	28.1
CCOM	32.1a	21.9a	27.2a	29.5
COMM	32.3a	–	27.9a	28.0
Fence row¶	46.1	36.4	35.6	

† 0N – no N fertilizer applied; N – N fertilizer applied; CSb – corn-soybean; CCOM – corn-corn-oat-meadow; COMM – corn-oat-meadow-meadow.
‡ 1957. Current SOC were significantly lower for all cropping systems except COMM.
§ Means within a column (location) with the same letter are not significantly different at the 0.05 level.
¶ Fence-row SOC shown for comparison. Relative SOC = cropping system SOC/fence-row SOC.

Several aspects of these management systems were probably responsible for the differences in SOC observed. Tillage promoted SOC decomposition by mixing the soil, disrupting aggregates, and incorporating residues. Tillage also promoted SOC losses through erosion by decreasing cover. Fewer tillage operations were a factor in the 4-yr rotations, because no tillage occurred from oat planting until the meadow crop was terminated. Thus, the soil was not tilled for 1.5 to 2.5 yr of the 4-yr cycle, residue decomposition was decreased, and cover was maintained. Bauer and Black (1981) also noted that SOC losses were less for systems with fewer tillage operations. Variation in species growth habits and differences in residue returned also contributed to the higher SOC observed in the rotations. Gosdin et al. (1949) found SOC was conserved when cereals or legumes were included in the rotation because they returned greater residue quantities to the soil than row crops. Wood et al. (1991) found that differences in SOC were a function of residue management on a Typic Hapludult, noting that rotations including corn had more SOC than those with soybean.

Continuous Corn Fertility Study

Relative organic C levels decreased with cropping during the first 35 yr of the study (Fig. 1). The decrease relative to initial SOC was affected by treatment. Manure treatments of 4.5 kg ha^{-1} yr^{-1} mediated SOC losses. The N-P-K rate study initiated in 1952 resulted in increases in relative SOC. The slight increase noticed in the unfertilized treatment could be attributed to use of improved hybrids, or to slight cyclical fluctuations in yields. Fertilizer applications increased SOC (Table 4). Other factors significantly affecting 1992 SOC were the 1952 (initial) SOC and replication. Two of the four replications received manure for 35 yr prior to the N-P-K rate study initiation. Effects of former management practices may linger for many years after adoption of a new management system. Nitrogen fertilizer rate on corn (range: 0–180 kg N ha^{-1} yr^{-1}) was not significant in determining SOC in this study, but only whether fertilization occurred. This result conflicts with the linear relationship between N and SOC found in winter wheat (*Triticum aestivum* L.) by Rasmussen and Rohde (1988), who used six rates (range: 11–50 kg N ha^{-1} yr^{-1}). Phosphorus and K fertilization did not significantly affect SOC.

Table 4. Probability of larger *F* values from covariance analysis of 1992 continuous corn soil organic carbon (SOC) at the Agronomy Farm, Ames, IA.

Source	*F* value	$P > F$
Replication†	4.59	0.0195
Fertilizer	5.74	0.0044
1952 SOC‡	52.01	0.0001
Contrasts: Zero rate vs. other rates		
N	4.79	0.0018
P-K	4.19	0.0598

† Each plot in the manure and lime study (1915–1952) constituted one replication of the fertility study (1952–1992).
‡ SOC at initiation of fertility study used as covariate for 1992 SOC.

When treatment averages were used to estimate residue yield, residue returned affected SOC more than initial SOC or fertility treatment at Sutherland ($P > F = 0.1030$) and in the N-P-K rate study ($P > F = 0.0911$), though neither was significant at the 0.05 level. Fertilizer increased biomass and grain yields, probably influencing SOC through residues returned. Wood et al. (1991) found that residue returned significantly affected SOC. On the manure-lime plots, only manure treatments significantly affected SOC ($P > F = 0.0329$) because annual manure applications (4.5 Mg ha^{-1} yr^{-1}) exceeded residues returned (4.1–4.4 Mg ha^{-1} yr^{-1}).

Residue returned ($P > F = 0.0022$) and location ($P > F = 0.0006$) significantly affected SOC. A regression equation for all sites was developed:

$$\text{SOC (g kg}^{-1}) = 20.5 + 0.301 \text{ annual residue returned (Mg ha}^{-1}) \qquad R^2 = 0.22$$

The fit was poor due to differences in SOC and residue relations among locations. Regression equations developed for each location more accurately described the data (Fig. 2). At all locations, SOC increased with greater

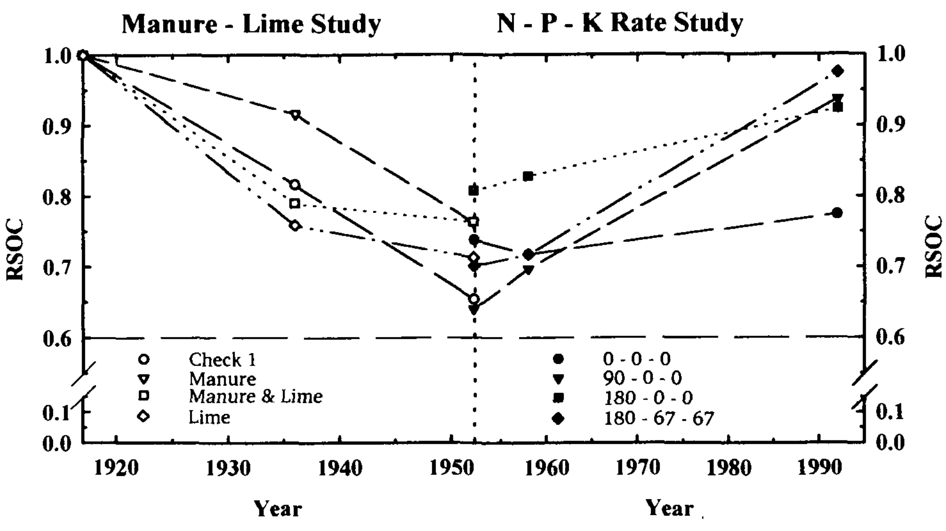

Fig. 1. Relative soil organic carbon (RSOC) with time, 1917 base year, Agronomy Farm, Ames, IA.

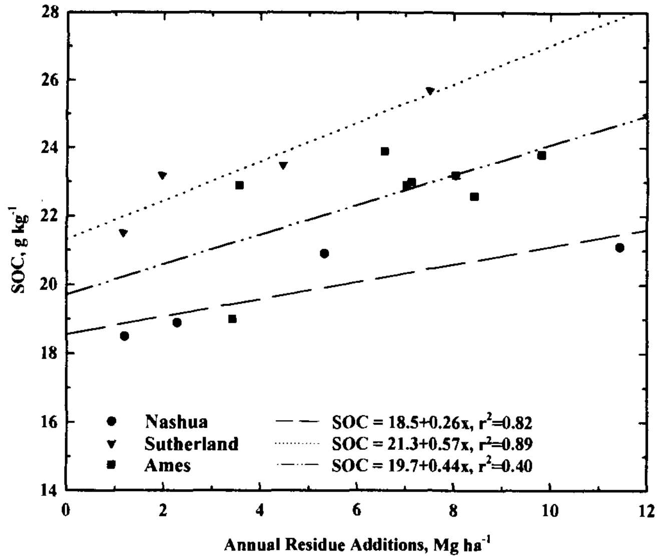

Fig. 2. Relation of soil organic carbon (SOC) to annual residue additions, by location.

quantities of residue returned. The regression for the N-P-K study at Ames was the weakest, probably because of the continuing influence of the manure-treated replications and the lack of plot yield data. Effects of precipitation differences between Sutherland and the other sites were masked by the fine particle sizes present at Sutherland, with only 2.6% sand.

In 1950, 4.8 million ha of corn and soybean were planted in Iowa, while a maximum of 9.1 million ha were planted in 1981 (Crop Reporting Board, 1994). An average of 8.9 million ha of corn and soybean are grown annually, accounting for 16% of the total land in corn and soybean in the USA (Conservation Tillage Information Center, 1990). The average SOC to 15-cm depth by use was row crops, 28.0 kg m^{-3}; 4-yr rotation, 32.6 kg m^{-3}; and fence row, 38.74 kg m^{-3}. These values, coupled with the acreage in row crop production, suggest that row crop land in Iowa has lost between 8.5 and 16.2 million Mg SOC since initiation of cropping. Conversion of row crop systems in Iowa to 4-yr rotations has the potential to sequester between 2.6 and 5 million Mg C as SOC in 20 to 30 yr, or 30% of the total SOC lost due to cropping. Such management would also decrease SOC decomposition and fossil fuel usage by decreasing tillage frequency.

Conservation of SOC should be a goal in production agriculture to decrease agricultural CO_2 emissions. It is possible to conserve SOC through appropriate choices of cropping, tillage, fertility, and residue management systems. Such management of SOC should decrease agricultural CO_2 emissions through reduced SOC decomposition, increased sequestering of atmospheric C, and reduced fossil fuel consumption. Conservation of SOC also is desirable to maintain yield potential (Bauer and Black, 1994; Lucas et al., 1977).

CONCLUSIONS

Cropping systems enhanced or diminished SOC. Unfertilized, monocrop systems were the most detrimental to SOC. Rotations with 2-yr meadows maintained the highest SOC and conserved the most SOC. In fertilized systems, and probably in the rotations, conservation of SOC was related to residue quantity returned to the soil. In the 4-yr rotations, decreased tillage intensity and variation in species growth habits were additional factors in SOC conservation. Conversion of row crop systems to 4-yr rotations has the potential to replace as much as 30% of the total SOC lost since cropping began in Iowa.

REFERENCES

Anderson, S.H., C.J. Gantzer, and J.R. Brown. 1990. Soil physical properties after 100 years of continuous cultivation. J. Soil Water Conserv. 45:117–121.

Bauer, A., and A.L. Black. 1981. Soil carbon, nitrogen, and bulk density comparisons in two cropland tillage systems after 25 years and in virgin grassland. Soil Sci. Soc. Am. J. 45:1166–1170.

Bauer, A., and A.L. Black. 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58:185–193.

Conservation Tillage Information Center. 1990. National survey of conservation tillage practices. Conserv. Tillage Inf. Center, Fort Wayne, IN.

Council for Agricultural Science and Technology. 1992. Preparing U.S. agriculture for global climate change. CAST Rep. 119. CAST, Ames, IA.

Crop Reporting Board. 1994. Crop production: 1993 summary. USDA Stat. Rep. Serv. U.S. Gov. Print. Office, Washington, DC.

Donald, C.M., and J. Hamblin. 1976. The biological yield and harvest index of cereals as agronomic and plant breeding criteria. Adv. Agron. 28:361–405.

Gebhart, D.L., H.B. Johnson, H.S. Mayeux, and H.W. Polley. 1994. The CRP increases soil organic carbon. J. Soil Water Conserv. 49:488–492.

Gosdin, G.W., M. Stelly, and W.E. Adams. 1949. The organic matter and nitrogen content and carbon–nitrogen ratio of Cecil soil as influenced by different cropping systems on Classes II, III, and IV land. Soil Sci. Soc. Am. Proc. 14:203–209.

Hageman, N.R., and W.D. Shrader. 1979. Effects of crop sequence and N fertilizer levels on soil bulk density. Agron. J. 71:1005–1008.

Havlin, J.L., D.E. Kissel, L.D. Maddux, M.M. Claassen, and J.H. Long. 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci. Soc. Am. J. 54:448–452.

Jenny, H. 1941. Factors of soil formation. McGraw-Hill, New York.

Kern, J.S., and M.G. Johnson. 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Sci. Soc. Am. J. 57:200–210.

Lucas, R.E., J.B. Holtman, and L.J. Conner. 1977. Soil and cropping practices. p. 333–351. *In* W. Lockeretz (ed.) Agriculture and energy. Academic Press, New York.

Mann, L.K. 1986. Changes in soil carbon storage after cultivation. Soil Sci. 142:279–288.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon and organic matter. p. 539–579. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Odell, R.T., S.W. Melsted, and W.M. Walker. 1984. Changes in organic carbon and nitrogen of Morrow Plot soils under different treatments, 1904–1973. Soil Sci. 137:160–171.

Rasmussen, P.E., and W.J. Parton. 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matter. Soil Sci. Soc. Am. J. 58:523–530.

Rasmussen, P.E., and C.R. Rohde. 1988. Long-term tillage and nitrogen fertilization effects on organic nitrogen and carbon in a semiarid soil. Soil Sci. Soc. Am. J. 52:1114–1117.

Salter, R.M. 1916. A rapid method for the accurate determination of total carbon in soils. J. Ind. Eng. Chem. 8:637–639.

SAS Institute. 1989. SAS/STAT user's guide. Version 6, 4th ed. Vol. 1 and 2. SAS Inst., Cary, NC.

Soon, Y.K., and S. Abboud. 1991. A comparison of some methods for soil organic carbon determination. Commun. Soil Sci. Plant Anal. 22:943–954.

Tabatabai, M.A., and J.M. Bremner. 1991. Automated instruments for determination of total carbon, nitrogen, and sulfur in soils by combustion techniques. p. 229–259. *In* K.A. Smith (ed.) Soil analysis, modern instrumental techniques. 2nd ed. Marcel Dekker, New York.

Unger, P.W. 1968. Soil organic matter and nitrogen changes during 24 years of dryland wheat tillage and cropping practices. Soil Sci. Soc. Am. Proc. 32:426–429.

U.S. Congress. 1991. Changing by degrees: Steps to reduce greenhouse gases. Rep. OTA-0-482. Office of Technol. Assessment, Washington, DC.

Voroney, R.P., J.A. Van Veen, and E.A. Paul. 1981. Organic C dynamics in grassland soils. 2. Model validation and simulation of long-term effects of cultivation and rainfall erosion. Can. J. Soil Sci. 61:211–224.

Wallace, A., G.A. Wallace, and J.W. Cha. 1990. Soil organic matter and the global carbon cycle. J. Plant Nutr. 13:459–466.

Winters, E., Jr., and R.S. Smith. 1929. Determination of total carbon in soils. Ind. Eng. Chem. Anal. Ed. 1:202–203.

Wood, C.W., J.H. Edwards, and C.G. Cummins. 1991. Tillage and crop rotation effects on soil organic matter in a Typic Hapludult of northern Alabama. J. Sustain. Agric. 2:31–41.

Yeomans, J.C., and J.M. Bremner. 1991. Carbon and nitrogen analysis of soils by automated combustion techniques. Commun. Soil Sci. Plant Anal. 22:843–850.