0038-075X/03/16812-888–899
Soil Science

December 2003
Vol. 168, No. 12
Printed in U.S.A.

SOIL PHYSICAL PROPERTIES AND CROP PRODUCTIVITY OF AN ERODED SOIL AMENDED WITH CATTLE MANURE

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Erosion changes soil properties, especially physical properties, mainly because it removes surface soil rich in organic materials and exposes lower soil layers. In 1988, a study was established to determine the effects of soil erosion and long-term manure applications on selected soil physical properties and corn (*Zea mays* L.) production. After 10 years of annual manure applications, soil core samples were collected in 7.6-cm increments at three depths, 0 to 7.6, 15 to 22.6, and 30 to 37.6 cm, to determine soil bulk density (ρ_b), hydraulic conductivity of saturated soil (K_s), and water retention. Bulk density and K_s increased slightly with erosion level. Water retention did not change in the surface 7.6 cm, but it did decrease with increasing erosion level at deeper depths. Long-term application of manure decreased ρ_b by 10%, whereas K_s was doubled in the top 7.6 cm of soil. Manure increased soil-water retention capacity and decreased differences in water retention between erosion levels, especially at low suctions (0 to 20 kPa). Soil carbon content correlated well with water retention and ρ_b. Corn grain yields in 1997, 1998, and 1999 were 15, 6, and 14% less, respectively, in the severe than in the slight erosion phase. Long-term manure additions increased corn grain yields by 19% in 1998 and by 25% in 1999. Increased yield from manure additions was likely related to an enhancement in water retention. Results from this study show that long-term manure application is a possible management alternative for restoring the physical properties and crop productivity of eroded soil. (Soil Science 2003;Volume 168:888–899)

Key words: Eroded soil restoration, cattle manure, physical properties, crop productivity.

EROSION often causes changes in the biological, chemical, and physical properties of soil. Changes in biological properties, especially microbiological properties, are usually difficult to measure and quantify. In addition, changes in chemical properties can be offset with fertilizer or pH-modifying inputs. Commercial fertilizers can improve plant production of most eroded soils and mask the effects of soil loss (Dormaar et al., 1988; Freeze et al., 1993; Cihacek and Swan, 1994; Larney et al., 1995; Larney and Janzen, 1996). However, permanent reductions in crop productivity of eroded soils are caused primarily by changes in soil physical properties (Frye et al., 1982; Ebeid et al., 1995; Fahnestock et al., 1995; Lowery et al., 1995; Shaffer et al., 1995), especially water retention.

The ability of soil to infiltrate and retain water is critical for plant production. Limited water retention can lead to insufficient water for plant uptake unless supplemental irrigation is used. Water retention is affected by particle and pore size distribution. Therefore, in eroded soils, one should expect decreased water retention because of the preferential removal of clay and silt size particles that occurs with erosion. However, if the lower soil horizons have a greater clay content

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[a] Mention of company or product name does not constitute endorsement by the USDA-ARS or the University of Wisconsin-Madison to the exclusion of others.

Received Dec. 17, 2002; accepted Aug. 18, 2003.

DOI: 10.1097/01.ss.0000106403.84926.7e

than the removed surface layers initially, soil water retention may increase, but not all this water will be plant-available (Andraski and Lowery, 1992). Under such eroded conditions, soil water is held strongly, and additional energy is needed for plant uptake when compared with uneroded conditions. Furthermore, as the erosional process continues and soil is severely eroded, energy requirements to extract water from the soil increase. Eroded soils are usually shallower and plant roots have less volume to exploit for water and nutrients compared with less eroded soils. For these reasons, some researchers have observed a decrease in the available soil water capacity of eroded soils, whereas others have reported no differences, and even increases, in the water retention ability of eroded soils (Frye et al., 1982; Ebeid et al., 1995; Fahnestock et al., 1995; Lowery et al., 1995). Therefore, by improving the physical properties of an eroded soil, it may be possible to ameliorate the harmful effects of erosion.

Greater organic matter contents have been linked to increased water retention capacity in soils (N'Dayegamiye and Angers, 1990; Tester, 1990; Droogers and Bouma, 1996; Warren and Fonteno, 1993), especially at soil saturation and field capacity water content. This is believed to be caused by enhanced aggregate formation resulting from organic substances. For this reason, organic matter additions can potentially be used to restore the water retention capacity of an eroded soil with diminished plant-available water.

Although many studies have been conducted regarding the effects of erosion on soil productivity, few have been conducted on the effects of long-term manure applications on the physical properties of eroded soil. For this reason, our first objective was to study the effect and severity of past erosion on soil physical properties and crop production, and our second was to determine if long-term manure applications can improve selected physical properties and crop productivity of an eroded soil.

MATERIALS AND METHODS

This study was conducted in the driftless region of southwestern Wisconsin at the Lancaster Agricultural Research Station of the University of Wisconsin-Madison (42° 52′ N, 90° 42′ W). The driftless region is an area covering parts of southwest Wisconsin, southeast Minnesota, northeast Iowa, and northwest Illinois that escaped glacial activity during the last ice age. Since this area did not experience the leveling effects of glaciers, soils in this region are characterized by steep slopes and are relatively vulnerable to erosion. The primary soil at the research site is a Dubuque silt loam (fine-silty, mixed, mesic, Typic Hapludalfs). Soils in this area were formed in loess underlain by a red clay residuum with a subangular blocky structure (Glocker, 1966). The study site was 120 by 60 m and located on a southwest-facing linear slope (10 to 14%). Alfalfa (*Medicago sativa* L.) was grown on this site for 5 years prior to this study. The entire site has been under continuous corn since 1984.

In 1985, three phases of past erosion (slight, moderate, and severe) were identified using the depth to the red clay residuum (2Bt2 horizon) as a reference layer. Reference layers are suitable for determining erosion severity using the guidelines from the Soil Survey Manual (Soil Survey Division Staff, 1993). Three 7.3- by 13.7-m plots were established for each of the three erosion phases. Depth to the red clay residuum was measured at seven locations in each plot and ranges from 0.45 to 0.95 m (Table 1) (Andraski and Lowery, 1992).

Tillage operations included chisel plowing in the fall and disking in the spring across the slope. Anhydrous ammonia was applied in the spring as pre-plant N fertilizer, and N, P, and K fertilizer was applied as a starter at planting. Pesticides to control weeds and insects were applied to the entire research site as needed.

A study of the effects of erosion on corn production was conducted from 1985 until 1988. Cattle manure applications were added in Fall 1988 to the bottom one-half of each plot across the slope, creating two subplots from each original plot. The first cattle manure slurry application was injected using a manure injector in the bottom half of the plots (downslope) to prevent

TABLE 1

Horizon depth and textural classification for three erosion phases of a Dubuque silt loam soil in 1985

Erosion phase	Soil horizon	Average depth	Textural class
		.... cm	
Slight	Ap	0–36	silt loam
	Bt1	36–95	silty clay loam
	2Bt2	95–>113	silty clay
Moderate	Ap	0–20	silt loam
	Bt1	20–74	silty clay loam
	2Bt2	74–>99	silty clay
Severe	Ap	0–17	silt loam
	Bt1	17–45	silty clay loam
	2Bt2	45–79	silty clay

(adapted from Andraski and Lowery, 1992) manure runoff from contaminating subplots receiving no manure. Manure applications were changed to solid cattle manure in Fall 1992 to assure a more uniform application of the manure (Table 2). Solid cattle manure was applied with a rear box manure spreader and incorporated into the soil with the Fall chiseling. Similar amounts of total N were applied to all subplots by reducing anhydrous ammonia applications in subplots receiving manure to compensate for manure N applied. The NPK starter fertilizer applied at planting was the same for all subplots.

Grain yield was determined by harvesting a 3-m section from each of the two middle rows of each subplot. Grain subsamples were dried for moisture determination. Grain yields were adjusted to a 15.5% moisture content. Stover yields were calculated from 10 plants collected from the two middle rows of each subplot. Subsamples were taken to determine moisture content, and yields were calculated on a dry matter basis. Corn grain and Stover yield data for 1997, 1998, and 1999 growing seasons are reported to correspond with the physical property and soil carbon data.

Soil particle size distribution (PSD) analysis was performed by the hydrometer method (Gee and Bauder, 1986). Samples used for particle size determination were collected in 1998 with a truck-mounted hydraulic push probe (Giddings Machine Co., Fort Collins, CO)[a] to a depth of 120 cm where possible. A soil core was collected from each subplot, stored in plastic sleeves with a 4.4-cm inner diameter, taken to the laboratory, and cut into 15-cm increments for PSD determination.

Although soil carbon content is not a physical property per se, it relates to many important soil physical properties. Total carbon analysis was performed on soil samples collected in June 1997 with a 1.9-cm diam. hand push probe to a depth of 50 cm in 10-cm increments. Five samples were taken from each subplot and depth increment and grouped to form one composite sample per depth for each subplot. Soil samples were oven-dried at 105 °C for 24 h. After drying, soil samples were ground by hand to pass a 100-mesh (149-μm openings) sieve. Total carbon determination was done by dry combustion with a Tekmar-Dohrman DC-190 carbon analyzer (Rosemount Analytical Inc., Dohrman Division, Santa Clara, CA) equipped with a solid sampler unit.

In August 1998, soil core samples were collected at three depths (0 to 7.6, 15 to 22.6, and 30 to 37.6 cm) for water retention, K_s, and ρ_b analyses. One sample per subplot at each depth was collected in aluminum cylinders. The cylinders were 7.6 cm in diameter and 7.6 cm long. After collection, each sample was placed first in a plastic bag and then in a cardboard cylinder container, taken to the laboratory, and refrigerated at 4 °C. Chloroform was used before refrigeration as a fumigant to eliminate further growth of organisms. For analysis purposes, a silk screen was placed on the bottom of each cylinder with rubber bands to minimize soil loss. Samples were placed in a plastic tub and the tub was filled with tap water to a depth equal to one-half the height of the cores. After at least 6 h, the tub was filled precisely to the top edge of the cylinders. After another 6-h period, samples were placed on a water-retention apparatus (McGuire and Lowery, 1992). Water release data were collected for a suction range of 0 to 20 kPa. Empty cylinders fitted with silk screens were used as blanks to correct for the water retention of the silk screen.

After removal from the water-retention apparatus, samples were placed in a falling head permeameter for K_s determination (Klute and Dirksen, 1986). Samples were then dried at 105 °C for 24 h and weighed for ρ_b determination following the K_s readings (Blake and Hartge, 1986).

TABLE 2

Manure loading rates from 1988 to 1998 at the Lancaster research site

Applied Cattle Manure Slurry

Cattle manure	1988	1989	1990	1991
	Mg ha^{-1}			
Loading rate†	7.5	10.8	16.7	27.4

Applied Solid Cattle Manure

Cattle manure	1992	1993	1994	1995	1996	1997	1998
	Mg ha^{-1}						
Loading rate†	14	NR‡	19.8	10	NR	11.9	13

†Reported as dry matter.

‡NR = manure applied but loading rate not reported.

Data were analyzed using analysis of variance (ANOVA) applying the generalized linear model (GLM) procedure in Statistical Analysis Systems (SAS) software (SAS Institute, 1989). Mean separation was performed using a least significant difference (LSD) multiple-range test procedure in SAS. Correlation analysis of soil total carbon content vs ρ_b, K_s, and volumetric water content at saturation (θ_{sat}) and at 20 kPa of suction (θ_{20kPa}) was conducted using the correlation procedure in SAS. It was assumed that carbon content did not change significantly from year to year and that carbon content and physical property values obtained were representative for each treatment since the experiment was located in a fairly uniform and linear slope. Total carbon contents at 3.8, 18.3, and 33.8 cm, which correspond to the center of the soil cores used for physical properties determination, were estimated by linear interpolation.

RESULTS AND DISCUSSION

Particle Size Analysis

The soil at the Lancaster research site is characterized by a clay-rich, soil residuum (2Bt2 horizon). Therefore, as erosion progressed at this site, the 2Bt2 horizon was closer to the surface. For this reason, depth to the 2Bt2 horizon has been used as a reference layer to determine the severity of past erosion at this site (Soil Survey Division Staff, 1993). Greater clay contents are observed at shallower depths with increasing soil erosion (Fig. 1). Sand content does not vary greatly between erosion levels, and, therefore, differences in particle size analysis among erosion levels result from changes in the silt and clay fractions.

Total Carbon

It is generally accepted that a recently eroded soil will have less carbon than it did before erosion. Thus, one expects carbon content to decrease with increasing erosion phase because of the incremental removal of organic matter in the surface soil. However, a soil that suffered erosion in the past and has not experienced significant erosion in recent times could accumulate organic matter in the surface soil layers. This seems to be the case for the soil at the Lancaster research site. Carbon content in the top 20 cm was greater in the severe phase, followed by the moderate and slight erosion phases, for the eroded soil not receiving manure (Fig. 2). Although these differences in total carbon content between erosion phases were not significant ($P = 0.37$), this trend of greater carbon content with increasing erosion phase follows the trend of greater clay content with increasing erosion phase. This is in agreement with Lowery et al. (1995), who reported increasing organic carbon content in the Ap horizon with increasing erosion severity at this site. However, at other locations in the Midwest, the reverse trend of decreasing carbon with increasing erosion has been reported (Lowery et al., 1995). Furthermore, there is evidence suggesting that clay particles are more interactive with organic matter than with sand and silt particles, promoting accumulation of organic materials in areas were there is a greater clay content (Mortland, 1970; Greenland, 1971; Bohn et al., 1985; Stevenson, 1994; Sparks, 1995). Most of the erosion that has occurred at the Lancaster site is believed to be from historical erosional events. Therefore, enough time has elapsed since the main erosional period for carbon to accumulate in the surface of the eroded soil. These factors explain the increasing carbon content with increasing erosion phase for the surface 20 cm of the soil profile. Deeper in the profile (>20-cm depth), the order of total soil carbon content changes to slight > severe > moderate.

Manure additions increased total carbon content significantly (P-values ranged from 0.01 to 0.13) for all erosion phases to a depth of 25 cm, and down to 35 cm for the severe erosion level (Fig. 3). Increases in carbon content with erosion phase in the top 25 cm relates well to management, since chisel plowing can mix the surface soil to near this depth. Therefore, it would be expected that any changes in ρ_b, K_s, or water retention caused by the manure applications would be limited mainly to the surface 25 cm of soil.

Bulk Density

Investigators have reported increases in ρ_b with increasing erosion phases (Frye et al., 1982; Ebeid et al., 1995; Fahnestock et al., 1995; Lowery et al., 1995). Since organic matter promotes aggregation and, thus, tends to reduce ρ_b, these increases in ρ_b in eroded soil are attributed to the loss of surface soil layers that contain higher levels of organic material. At the Lancaster site, differences in ρ_b between erosion phases for soil not receiving manure are minimal (Fig. 4). There are three factors that may explain the lack of trend in ρ_b between erosion phases at this site. First, tillage operations probably offset any potential differences in ρ_b near the surface between erosion phases. In addition, soils with greater clay content

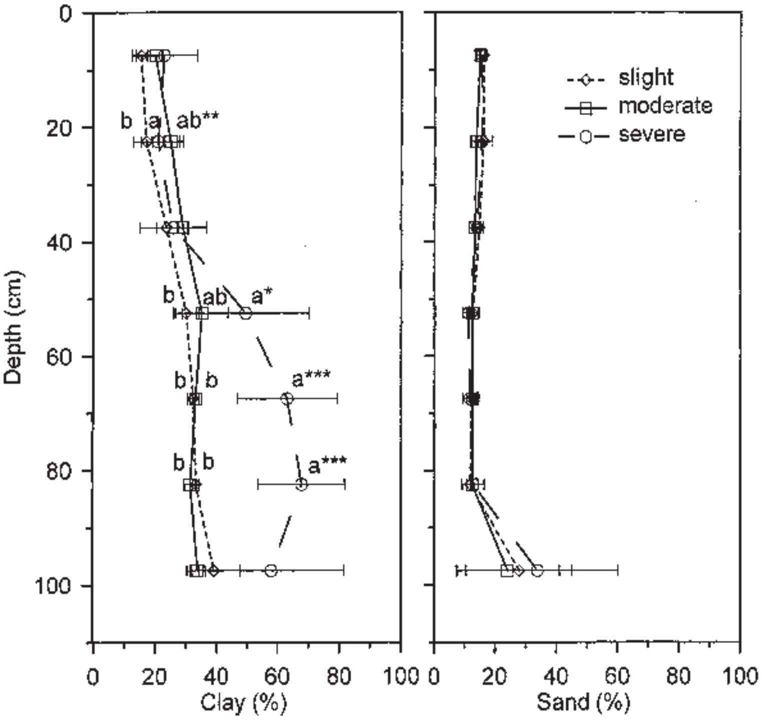

Fig. 1. Changes in clay and sand content with depth for the three erosion levels. Least significant difference mean separations between the erosion level at each depth are represented with letters and significance levels that correspond to Pr > F of <0.01, 0.05, or 0.10 are represented by ***, **, or *, respectively. Error bars represent the standard deviations at each depth.

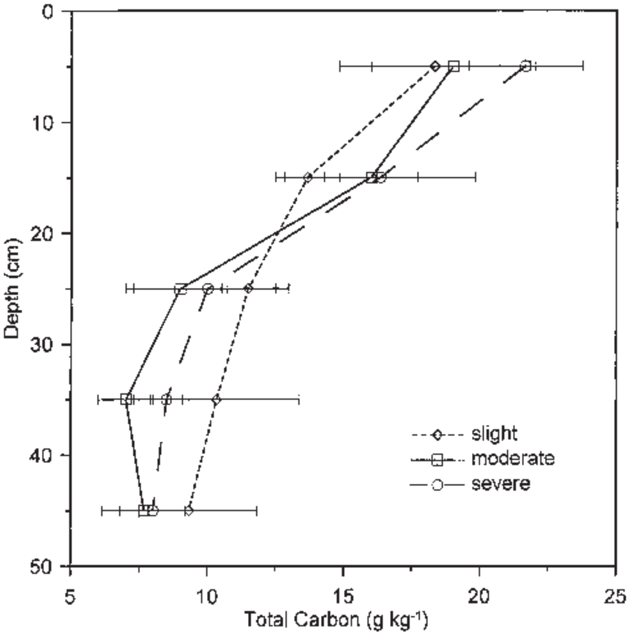

Fig. 2. Soil carbon distribution with depth for slight, moderate, and severe erosion levels. Error bars represent the standard deviations at each depth.

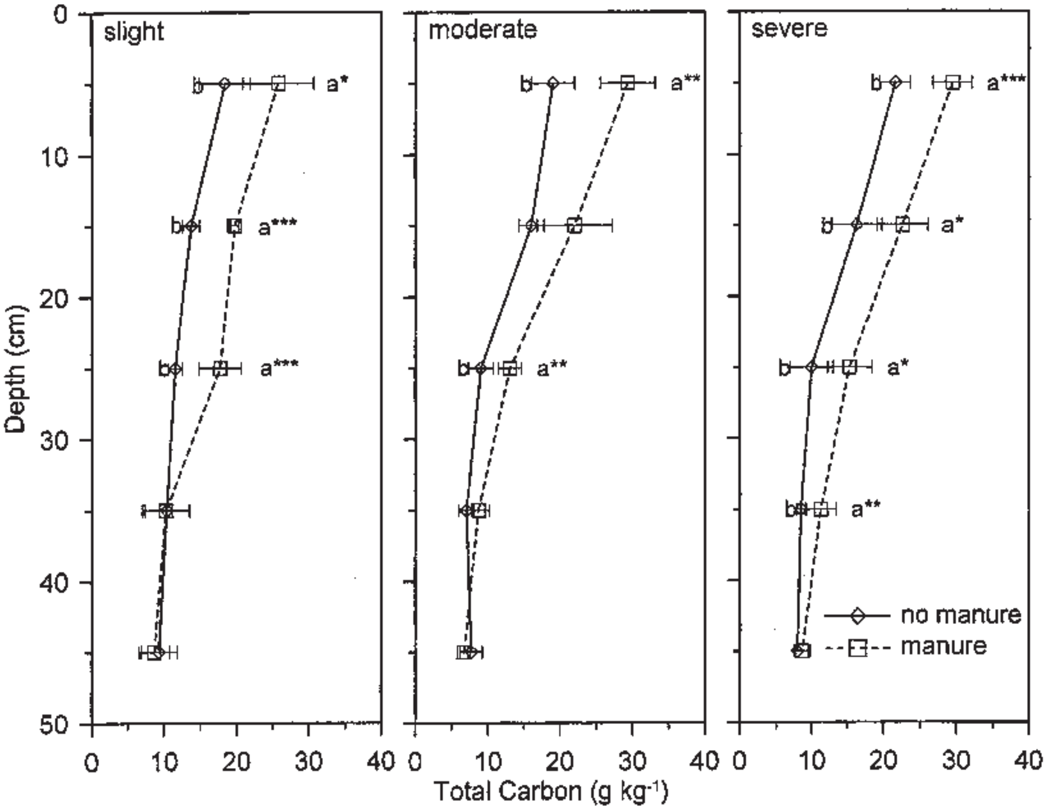

Fig. 3. Soil carbon distribution for manured and un-manured soil from slight, moderate, and severe erosion levels. Least significant difference mean separations between erosion level at each depth are represented with letters and significance levels that correspond to Pr > F of <0.01, 0.05, or 0.10 are represented by ***, **, or *, respectively. Error bars represent the standard deviations at each depth.

have lower ρ_b values if not compacted, and, as mentioned previously, there is a trend of increasing clay content with increasing erosion severity at this location. Finally, soil carbon content in the surface soil is greater in the severe and moderate erosion phases than in the slight. Although these differences in carbon content are small, they have an impact on soil ρ_b. These three factors combined contribute to the lack of trend in ρ_b between erosion phases at this site.

Long-term manure applications reduced ρ_b in the top layers of the eroded soil (Fig. 4). Manure application reduced ρ_b significantly in the slight erosion phase at 0- to 7.6-cm ($P = 0.07$) and 15- to 22.6-cm ($P = 0.07$) depths. Probability values for the moderate and severe erosion phases at the 0- to 7.6-cm depth were 0.29 and 0.24, and at 30- to 37.6-cm depth values were 0.78 and 0.42, respectively. Reductions in ρ_b can be attributed to an increase in organic matter content as a result of the manure applications. There is evidence showing that adding organic materials to soil reduces ρ_b (Martens and Frankenberger, 1992; Jordahl and Karlen, 1993; Girma and Endale, 1995; Obi and Ebo, 1995). Inexplicably, ρ_b seems to increase with manure applications at the 30- to 37.6-cm depth. Greater ρ_b values were observed in the manured subplots of all three erosion phases at the 30- to 37.6-cm depth when compared with the nonmanured subplots. One possibility is that the equipment used to apply the manure caused sub-soil compaction.

Hydraulic Conductivity of Saturated Soil

Although changes in ρ_b at the study site were minimal, differences in K_s between erosion phases of soils not receiving manure were more noticeable. Hydraulic conductivity of saturated soil at the 0- to 7.6-cm depth was not significant among

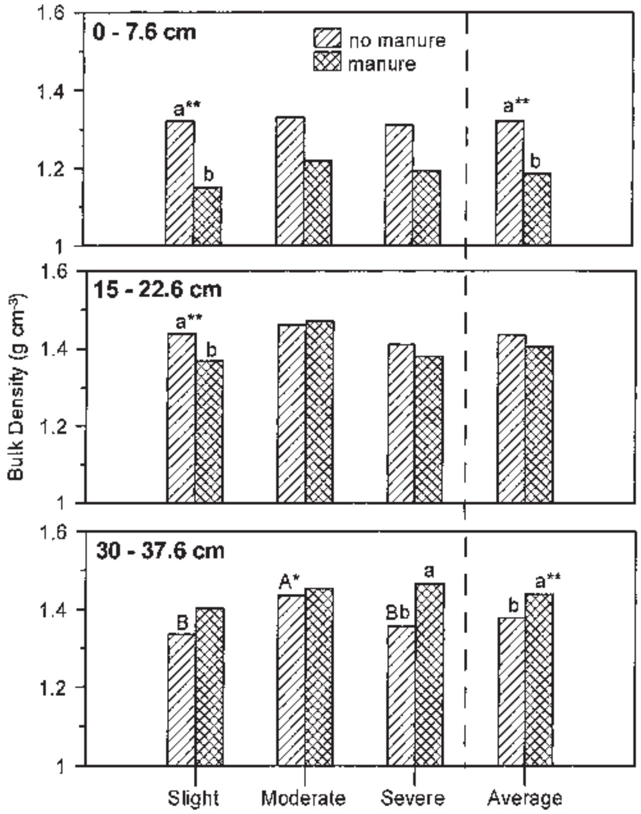

Fig. 4. Soil bulk density at 0- to 7.6-, 15- to 22.6-, and 30- to 37.6-cm for slight, moderate, and severe erosion levels, as well as an average of the three erosion levels. Least significant difference mean separation is represented with letters. Capital letters show significance between erosion levels, and small case letters show significance between manure treatments. Significance levels that correspond to Pr > F of <0.01 and 0.05 are represented by ***, and **, respectively.

the erosion phases (P = 0.74) (Fig. 5). From the 30- to 37.6-cm depth, the severe erosion phase had significantly (P = 0.03) greater K_s than the slight and moderate phases. A possible explanation is that greater clay and carbon contents with increasing erosion severity may have enhanced macropore and aggregate formation and, thus, increased K_s. However, at the 15- to 22.6-cm depth there were no differences in K_s among erosion phases (P = 0.50).

Subplots receiving manure applications had greater K_s values at the measured depths when compared with subplots not receiving manure. The only statistically significant difference (P = <0.01), however, was in the severe erosion level at 15 to 22.6 cm. Probability values for other erosion phases and depths ranged from 0.21 to 0.67. The increase in K_s in those areas receiving manure seems to be related to increased carbon content in the soil and, possibly, greater organism activity such as earthworms.

Soil Water Retention

Differences in soil water retention at the range of suction measured (0 to 20 kPa) were affected primarily by variations in secondary soil structure and, to a lesser extent, changes in particle size distribution. The severe erosion phase had the greatest volumetric water content at saturation for all measured depths, followed by moderate and then slight erosion phases (Fig. 6). The trend of greater water content at saturation with increasing erosion phase follows the trend of increasing carbon and clay content with increasing erosion phase in the upper soil layer. Water release curves between erosion phases for soil not receiving manure were similar in the top soil layers (Fig. 6). As tension increased to 20 kPa, dif-

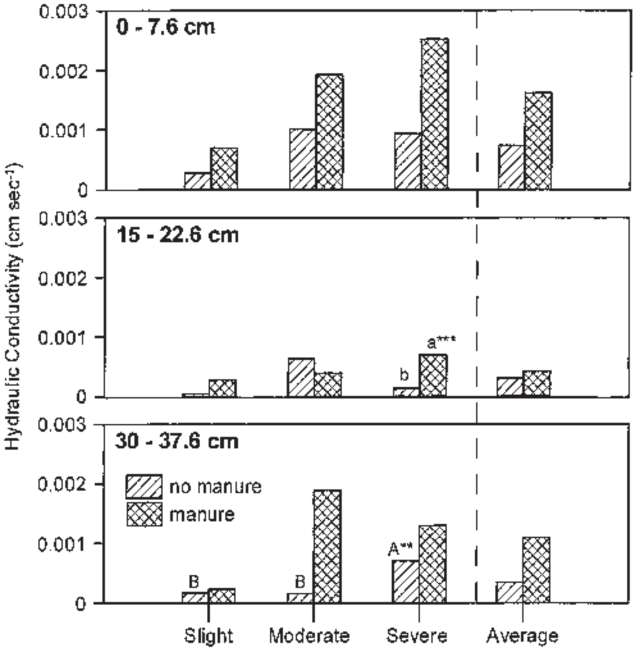

Fig. 5. Hydraulic conductivity of saturated soil at the 0- to 7.6-, 15- to 22.6-, and 30- to 37.6-cm depth. Least significant difference mean separation is represented with letters. Capital letters show significance between erosion levels, and small case letters show significance between manure treatment at Pr > F of <0.01, and 0.05 represented by ***, and **, respectively.

ferences in water release were greater, with the severe erosion phase having the lowest water content. This trend follows the general idea that as erosion severity increases, less water is available for plant uptake. However, at 30 to 37.6 cm, the moderate erosion phase had greater water retention capacity than the slight and severe erosion phases. At the 30- to 37.6-cm depth, variability in soil water retention between erosion levels was greater than at shallower depths.

Manure additions decreased differences in water retention between erosion levels. The variability in water retention was also decreased with manure applications between the 15- to 22.6- and the 30- to 37.6-cm depths. These observations provide evidence of the restorative effects of manure applications to eroded soil.

Soil water retention from 0 to 7.6 cm increased significantly with manure additions for the slight ($P = 0.06$) and moderate ($P = 0.03$) erosion phases, but not for the severe phase ($P = 0.12$), where water retention increased, although not significantly. Nevertheless, overall gains in soil water retention from manure applications in the severe erosion phase were greater than for the other two erosion levels. Manure additions increased water retention capacity at all depths tested in the severely eroded areas, with the surface 7.6 cm having the greatest increase. This trend in water retention can be attributed to increased organic matter content in the surface soil from manure additions and greater clay content with increasing erosion, particularly since organic matter improves aggregation (Weill et al., 1988; Martens and Frankenberger, 1992) and clay particles interact with organic matter, further augmenting aggregation (Bohn et al., 1985; Greenland, 1971; Mortland, 1970; Sparks, 1995; Stevenson, 1994).

Correlation Analysis

Correlation analysis revealed a strong relationship between total soil carbon and physical soil properties at sampled depths (Table 3). Soil bulk density had a significant negative correlation with total carbon in the upper 0 to 7.6 and 15 to 22.6 cm, whereas the correlation was positive, but not significant, at the 30- to 37.6-cm depth. This discrepancy is caused by the increase in ρ_b values observed in the manured subplots at the 30-

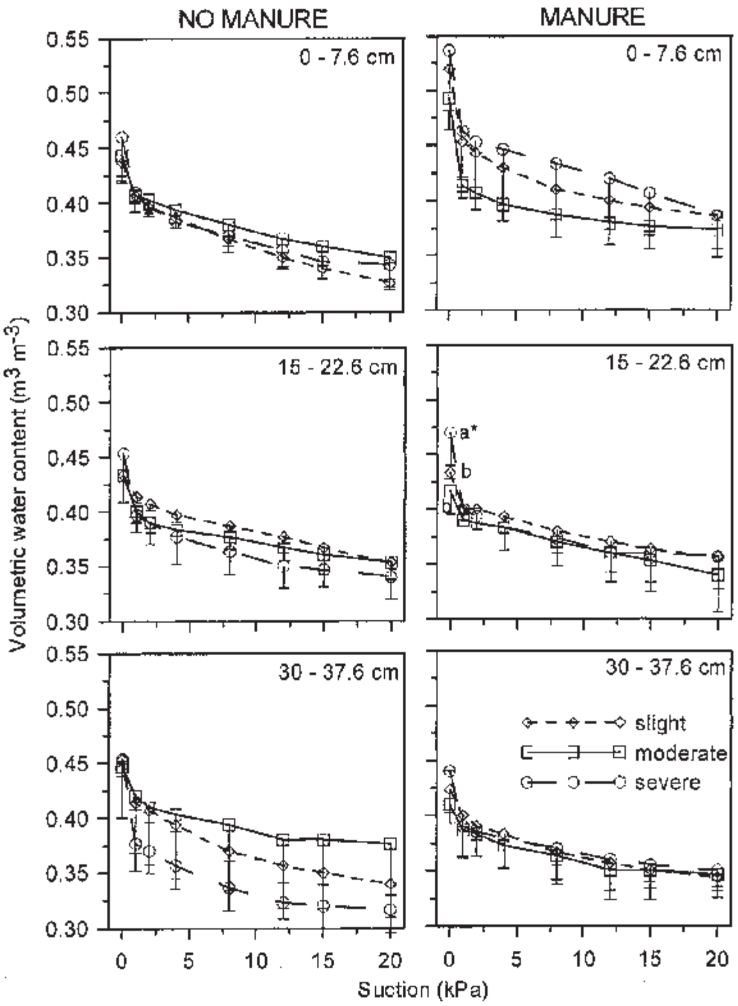

Fig. 6. Soil water release curves at the 0- to 7.6-, 15- to 22.6-, and 30- to 37.6-cm depth. Error bars represent the standard deviations at each suction interval.

to 37.6-cm depth. Similarly, correlation factors were not strong for the moderate erosion phase at any of the depths. Long-term manure applications seem to have little effect on ρ_b in the moderate erosion phase.

The amount of total carbon in the soil seems to have little correlation with K_s. There was good correlation with K_s for the slight erosion phase at the 15- to 22.6-cm depth and with the severe and moderate phases at the 30- to 37.6-cm depth. The high variability inherent in K_s measurements was most likely the cause for the lack of correlation.

Volumetric water contents at saturation (θ_{sat}) and at 20 kPa (θ_{20kPa}) of suction were selected to be representative of the soil water retention inasmuch as they are at the beginning and end of the suction range for the water retention curves discussed here. A high correlation was observed between total carbon and water contents at both levels of suction. At θ_{sat} in the surface 7.6 cm, there was a strong positive correlation with total carbon for all erosion phases. However, from 15 to 22.6 and 30 to 37.6-cm, the correlations were significant only for the moderate and severe erosion phases, possibly indicating that the effects of erosion were minimal in the slight phase. From 15 to 22.6-cm, the correlation in the moderate erosion phase is negative, but the correlation is positive for the severe phase. A positive correla-

TABLE 3

Probability levels and corresponding *P* values (in parenthesis) from correlation analysis for total carbon versus soil bulk density (ρ_b), hydraulic conductivity of saturated soil (K_S), volumetric water content at saturation (θ_{sat}), and at 20 kPa of suction (θ_{20kPa})

Depth	Erosion phase	Total carbon			
		ρ_b	K_S	θ_{sat}	θ_{20kPa}
...... cm					
0–7.6	Slight	−0.8224 (<0.01)	0.3773 (0.23)	0.7729 (<0.01)	0.9234 (<0.01)
	Moderate	−0.4347 (0.16)	0.2419 (0.45)	0.6270 (0.03)	0.3536 (0.26)
	Severe	−0.8263 (<0.01)	0.4891 (0.15)	0.9212 (<0.01)	0.7998 (<0.01)
	All phases	−0.6380 (<0.01)	0.3835 (0.03)	0.7504 (<0.01)	0.7081 (<0.01)
15–22.6	Slight	−0.8893 (<0.01)	0.6151 (0.06)	0.2731 (0.39)	0.2454 (0.44)
	Moderate	−0.1744 (0.59)	−0.5549 (0.06)	−0.7003 (0.01)	−0.8034 (<0.01)
	Severe	−0.6231 (0.03)	0.1976 (0.58)	0.5800 (0.05)	0.2532 (0.43)
	All phases	−0.5030 (0.01)	−0.1684 (0.36)	0.1415 (0.41)	−0.1750 (0.31)
30–37.6	Slight	0.1880 (0.56)	0.3980 (0.20)	0.1183 (0.71)	0.6573 (0.02)
	Moderate	0.5296 (0.08)	0.7374 (0.01)	−0.7973 (<0.01)	−0.5052 (0.09)
	Severe	0.5670 (0.07)	−0.8782 (<0.01)	−0.6259 (0.04)	0.6307 (0.04)
	All phases	0.0163 (0.93)	0.0773 (0.67)	−0.1729 (0.32)	−0.1283 (0.46)

tion would indicate that there is an increase in water content as carbon content increases, whereas the opposite is true for a negative correlation. The case of negative correlations is difficult to explain at this time. Similarly, θ_{20kPa} are positively correlated to carbon content in the upper 7.6 cm of soil and at 30 to 37.6-cm for the slight and severe erosion phases. Strong negative correlations were observed in the moderate erosion phase at 15 to 22.6 and 30 to 37.6-cm. Overall, differences in carbon content were significant to a 30-cm depth, and manure applications had an impact on soil physical properties below this depth.

Corn Yield

Corn grain yields were lower in the severe erosion phase than in the slight erosion phase in 1997, 1998, and 1999 (Fig. 7). In 1997, grain yield differences between erosion levels were less marked, but this can be attributed to differences in the May–October rainfall. Although rainfall amounts in both growing seasons were similar, 60 cm in 1997 and 65 cm in 1998, rainfall distribution was quite different. The month of July was drier in 1998, receiving less rainfall than in 1997 and with most of the rain occurring the first week of the month. In addition, June 1998 was slightly drier than June 1997. Corn plants in plots with greater erosion could have suffered some water stress during this 1998 period, reflected in the differences in grain yield. Low grain production in 1999 can be attributed to a low rainfall amount from May to October (54 cm). In any case, these decreases in grain yield provide further evidence of the damaging effects of erosion on crop productivity. A similar trend was noted by Arriaga and Lowery (2002), where the long-term effect of soil erosion reduced corn grain yield potential, and corn grain yields were more sensitive to changes in water storage as erosion severity increased. The 1997 and 1999 stover yields were also much less in the severe than in the slight and moderate erosion phases. No major differences ($P = 0.37$) between erosion levels in stover yield were noted in 1998 .

Manure applications had a positive impact on average yield, possibly from an increase in soil carbon content and associated changes in water retention and other physical properties. In 1998 and 1999, significantly greater average grain ($P = <0.01$ both years) and average stover ($P = 0.02$ and 0.03, respectively) yields in subplots receiving manure demonstrate that manure has the potential to improve corn production in eroded soils. In addition, the restorative effects of manure would likely have been greater if the manure had been incorporated to greater depths in the soil profile. This would have allowed a greater volume of the corn roots to grow in the soil with better conditions for plant growth.

CONCLUSIONS

Soil erosion is harmful for crop production and the environment. Environmental impacts, as well as additional losses in soil crop productivity,

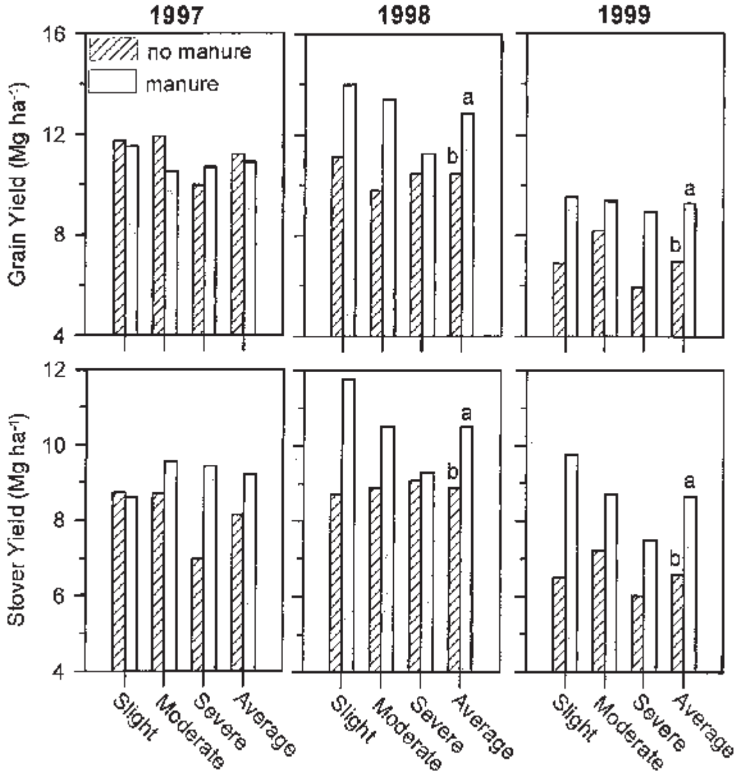

Fig. 7. Corn grain and stover yields for slight, moderate, and severe erosion phases, as well as the average of the three erosion phases. Least significant difference mean separation between un-manured and manured treatments are represented with letters at a probability of <0.03.

can be decreased with management practices that strive to reduce soil erosion in the first place. However, the decrease in productivity of an eroded soil can be long term. We have presented data indicating that erosion has an impact on soil productivity, most likely caused by deterioration in soil physical properties. Particle size, carbon distributions, ρ_b, and K_s are all changed in an eroded soil. More importantly, these factors are related to the ability of the soil to retain water. Adequate soil-water retention is critical for plant production. In the soil we studied, there was a slight trend of decreasing soil-water retention with increasing erosion phase. Because this study dealt with erosion from past events, the soil might have had enough time to reach a new equilibrium. This is noted by the relatively high carbon contents in all three erosion phases. For this reason, differences in the soil physical parameters measured were not very large. However, there was a high correlation between soil carbon content, ρ_b, and water retention. Long-term manure applications (i.e., increasing soil carbon content) improved the water retention of the eroded soil, and, subsequently, corn yield was also improved. For this reason we believe that continuous application of some carbon sources, such as cattle manure, may be a good method for restoring the productivity of eroded land.

ACKNOWLEDGMENT

Research support from North Central Regional Project (NC-174) is greatly appreciated. Thanks also to Carol Duffy for her assistance with manuscript editing.

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