0038-075X/06/17106-468–482
Soil Science

June 2006
Vol. 171, No. 6
Printed in U.S.A.

RAPID CHANGES IN SOIL CARBON AND STRUCTURAL PROPERTIES DUE TO STOVER REMOVAL FROM NO-TILL CORN PLOTS

Humberto Blanco-Canqui[1], R. Lal[1], W. M. Post[2], R. C. Izaurralde[3], and L. B. Owens[4]

Harvesting corn (*Zea mays* L.) stover for producing ethanol may be beneficial to palliate the dependence on fossil fuels and reduce CO_2 emissions to the atmosphere, but stover harvesting may deplete soil organic carbon (SOC) and degrade soil structure. We investigated the impacts of variable rates of stover removal from no-till (NT) continuous corn systems on SOC and soil structural properties after 1 year of stover removal in three soils in Ohio: Rayne silt loam (fine-loamy, mixed, active, mesic Typic Hapludults) at Coshocton, Hoytville clay loam (fine, illitic, mesic Mollic Epiaqualfs) at Hoytville, and Celina silt loam (fine, mixed, active, mesic Aquic Hapludalfs) at South Charleston. This study also assessed relationships between SOC and soil structural properties as affected by stover management. Six stover treatments that consisted of removing 100, 75, 50, 25, and 0, and adding 100% of corn stover corresponding to 0 (T0), 1.25 (T1.25), 2.50 (T2.5), 3.75 (T3.75), 5.00 (T5), and 10.00 (T10) Mg ha^{-1} of stover, respectively, were studied for their total SOC concentration, bulk density (ρ_b), aggregate stability, and tensile strength (TS) of aggregates. Effects of stover removal on soil properties were rapid and significant in the 0- to 5-cm depth, although the magnitude of changes differed among soils after only 1 year of stover removal. The SOC concentration declined with increase in removal rates in silt loams but not in clay loam soils. It decreased by 39% at Coshocton and 30% at Charleston within 1 year of complete stover removal. At the same sites, macroaggregates contained 10% to 45% more SOC than microaggregates. Stover removal reduced >4.75-mm macroaggregates and increased microaggregates ($P < 0.01$). Mean weight diameter (MWD) and TS of aggregates in soils without stover (T0) were 1.7 and 3.3 times lower than those in soils with normal stover treatments (T5) across sites. The SOC concentration was negatively correlated with ρ_b and positively with MWD and LogTS. Stover removal at rates as low as 1.25 Mg ha^{-1} reduced SOC and degraded soil structure even within 1 year, but further monitoring is needed to establish threshold levels of stover removal in relation to changes in soil quality. (Soil Science 2006;171:468–482)

Key words: Stover removal, no-till, bulk density, soil organic carbon, tensile strength, aggregate stability.

[1]Carbon Management and Sequestration Center, FAES/OARDC, School of Natural Resources, The Ohio State University. Dr. Blanco-Canqui is corresponding author. 210 Kottman Hall, 2021 Coffey Rd., Columbus, OH 43210-1085. E-mail: blanco.16@osu.edu

[2]Environmental Sci. Div., Oak Ridge National Laboratory, Oak Ridge, TN 37831.

[3]Joint Global Change Research Institute, 8400 Baltimore Ave., Suite 201, College Park, MD 20740-2496.

[4]USDA-ARS, North Appalachian Experimental Watershed, P.O. Box 488, Coshocton, OH 43812.

Received Sep. 12, 2005; accepted Jan. 20, 2006.

DOI: 10.1097/01.ss.0000209364.85816.1b

THERE is a strong interest in harvesting corn stover for biofuel production. The use of stover as a renewable energy source may be beneficial to palliate the excessive dependence on conventional fuels and reduce CO_2 emissions into the atmosphere (Pacala and Socolow, 2004). Intensive and large-scale harvesting of stover for biofuel production may, however, have detrimental effects on soil organic carbon (SOC) sequestration and structural properties, thus adversely affecting agricultural productivity (Wilhelm et al., 2004). Although dubbed by some as "waste" and "short-lived" material, crop residue left on the soil surface is vital to soil life (Lal, 2004). It moderates soil temperature dynamics, increases soil-water storage and retention, reduces soil surface sealing and crusting, improves water and air flow, recycles nutrients, and reduces soil erosion and nonpoint source pollution (Karlen et al., 1994; Wilhelm et al., 2004).

It is possible that a small fraction of the total stover produced in the U.S. Corn Belt can be removed as biofuel (Wilhelm et al., 2004). Quantitative effects of the threshold levels of stover removal for different soils based on the stover needs to enhance SOC sequestration, control soil erosion, and improve soil structural properties have not, however, been well documented. In some soils, harvesting of excess corn stover may positively impact crop production because high stover retention slows soil warming in spring, thereby retarding seed germination, stunting plant growth, and often reducing crop yields (Arshad and Azooz, 2003). Thus, a balance between stover removal for biofuel and its retention for soil quality improvement needs to be established for soil-specific conditions.

Decline in SOC concentration and deterioration of soil structural properties as a result of stover removal can be significant, but information on the rate and magnitude of changes in these dynamics properties due to stover removal across diverse soils is not well known. Reports of long-term studies (>10 years) in the midwestern U.S. Corn Belt region including those from Iowa (Larson et al., 1972), Indiana (Barber, 1979), Minnesota (Allmaras et al., 2004; Wilts et al., 2004), and Wisconsin (Karlen et al., 1994) have shown that stover removal reduces the SOC concentration. In other regions, reductions in SOC concentration due to stover removal may, however, be small or not significant (Hooker et al., 2005). Thus, further studies are warranted to determine the magnitude of the effects of stover removal effects on SOC and on soil structural properties across diverse soils and management practices.

Adverse effects of stover removal on SOC and soil structure are often measurable after 3 to 5 years of continuous stover removal. In some ecosystems, however, changes in soil properties as a result of stover removal may be rather rapid and significant. Information on how rapidly the SOC and structural properties are altered by stover removal in no-till (NT) systems is not well documented. Degradation of soil aggregates can be rapid when soil surface conditions are altered (Karlen et al., 1994). Knowledge about the degree to which the SOC concentration changes over a short period (i.e., 1 year) after stover removal is vital to understanding soil processes and estimating short-term implications of stover removal.

Stability and strength of aggregates moderate soil physical quality and are fundamental to root growth, water and air movement, and crop production. Stover removal reduces the protective cover and supply of binding agents essential to soil aggregation. Thus, any removal of stover would negatively affect soil aggregation and SOC, but the effects may vary with soil, management, and climate. Studies on SOC and soil aggregation and their relationships under different tillage and cropping systems are many (Allmaras et al., 2004; Puget et al., 2005), however, independent effects of differing levels of stover removal on SOC concentration and soil aggregate properties within the same tillage system (e.g., NT) have not been widely studied. Thus, a need exists for a greater understanding of the stover removal effects on soil properties within a short period of removal from NT systems, which are prime candidates for stover harvesting. Therefore, the objectives of this experiment were to (1) determine the impacts of stover removal at different rates from NT continuous corn systems on SOC and structural properties of aggregates of three soils in Ohio and (2) assess relationships between SOC and soil structural properties as affected by stover management. The study was based on the hypothesis that corn stover removal causes rapid and significant changes in SOC and structural properties even within 1 year because of the strong alterations in soil temperature and moisture regimes and input of the biomass C returned to the soil. In this study, the term "stover" refers to the nongrain part of a corn plant that is left on the soil surface after harvest, such as stalk, husk, leaves, and cobs. Stover differs slightly from residue because residue includes plant materials that have been partly incorporated into the soil by traffic, tillage, and biological activities (Wilhelm et al., 2004). The term "stover" has often been used to refer to corn biomass (Tally, 2002; Kim and Dale, 2005).

MATERIALS AND METHODS

Site and Treatment Descriptions

This study was conducted in the ongoing NT experiments at three sites in Ohio. The project was initiated in May 2004 to determine the impacts of corn stover removal on soil physical quality, corn and biomass yield, and SOC concentration under NT continuous corn. The three experimental sites were (1) North Appalachian Experimental Watersheds near Coshocton, (2) Western Agricultural Experiment Station near South Charleston, and (3) Northwestern Agricultural Experiment Station near Hoytville. Soils of these sites differ in their texture, slope, and history of tillage and crop management (Table 1). The baseline data collected from the three sites just before (May 2004) the imposition of stover management is shown in Table 2.

A randomized complete block design with six treatments replicated thrice for a total of 18 plots of 3 × 3 m was laid out at each site in May 2004. The six treatments consisted of removing 100, 75, 50, 25, and 0, and adding 100% of corn stover corresponding to 0 (T0), 1.25 (T1.25), 2.50 (T2.5), 3.75 (T3.75), 5.00 (T5), and 10.00 (T10) Mg ha^{-1} of stover, respectively. The T10 is thus an addition of stover that doubles the normal rate of stover left in NT soils. The percent stover mulch cover in each plot was estimated using the line-transect method (Sloneker and Moldenhauer, 1977). Each plot after stover distribution was planted to corn in May 2004, and then any stover shift during planting was redistributed to the corresponding plots at the desired rates. Plots were borderless and the individual plots were only demarcated at the corners by marking flags to reduce any interference with planting and harvesting operations across plots. Each plot comprised four rows of corn spaced 0.75 m apart. Plots were managed similarly under NT continuous corn across the three sites. Weeds were controlled using 4 L ha^{-1} of alachlor [2-Chloro-2-6-diethyl-phenyl)-*N*-(methoxymethyl)-acetamide] and 2 L ha^{-1} of metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] at Coshocton; 2 L ha^{-1} of atrazine [6-chloro-*N*-ethyl-*N*(1-methylethyl)-1,3,5-triazine

TABLE 1

Soil and management characteristics of the three study sites

Study sites	Coordinates	Soil series	Taxonomic classification	Soil description	Slope, %	Management history
North Appalachian Experimental Watersheds, Coshocton, OH	40°16'19"N and 81°51'35"W	Rayne silt loam	Fine loamy, mixed, active, mesic Typic Hapludults	Deep and well drained soils formed from weathered shale and fine-grained sandstone	10	33-year NT continuous corn
Western Agricultural Experiment Station, South Charleston, OH	39°49'31"N and 83°38'04"W	Celina silt loam	Fine, mixed, active, mesic Aquic Hapludalfs	Very deep, moderately well drained and formed in high-lime loamy till plains and moraines	2	15-year NT continuous corn/soybean rotation
Northwestern Agricultural Experiment Station, Hoytville, OH	41°1124"N and 83°47'05"W	Hoytville clay loam	Fine, illitic, mesic Mollic Epiaqualfs	These soils are on a nearly level and on till-floored lake plains, very deep, and very poorly drained	<1	8-year continuous corn/soybean rotation under NT with alternate year disking

based on the assumption that aggregates are homogeneous, isotropic, and have a uniform deformation. The aggregate diameter was determined by two methods (Dexter and Kroesbergen, 1985). The first method (Method 1) consisted of averaging the diameter of upper (s_1) and lower (s_2) sieve sizes using Eq. (2)

$$Method\,1: d_{agg} = \frac{s_1 + s_2}{2} \qquad (2)$$

The second method (Method 2) consisted of measuring the diameter of each aggregate with a caliper in addition to using Method 1 for comparison purposes. The longest (d_1), intermediate (d_2), and smallest (d_3) diameter of each aggregate were used to estimate the d_{agg} using Eq. (3). Differences in d_{agg} between Method 1 and Method 2 were not significant.

$$Method\,2: d_{agg} = \frac{d_1 + d_2 + d_3}{3} \qquad (3)$$

Because of the high variability, TS was determined on 9 replicate aggregates per treatment for a total of 486 aggregates (18 treatments × 9 reps × 3 sites = 486). Air-dry aggregates were used to determine TS rather than oven-dry (Watts and Dexter, 1997) or moist aggregates equilibrated at different suction heads (Munkholm and Kay, 2002). Use of air-dry aggregates for characterizing TS is a common procedure (Imhoff et al., 2002). For the determination of baseline data on soil properties, bulk and core soil samples were collected from all plots in May 2004 before the establishment of stover treatments. These samples were analyzed for SOC concentration, particle-size distribution, ρ_b, WSA, and TS of aggregates using the procedures as explained above. Particle-size distribution was determined by the hydrometer method (Gee and Or, 2002).

Statistical Analyses

A one-way analysis of variance model was used to test whether differences in SOC of the whole soil, ρ_b, MWD, and TS among stover treatments were significant. A split-plot design with stover treatments as main plots and aggregate-size fractions as sub-plots was used to determine treatment effects on SOC by aggregate size and WSA. Data on TS were not normally distributed in accord with similar studies (Munkholm and Kay, 2002), and thus, data analyses were performed using log-transformed values to reduce the variance. Simple correlations and regressions were used to study the soil properties versus stover rate relationships. All analyses were conducted using the SAS statistical software (SAS Institute, 1999).

RESULTS

Concentration and Pool of Total Soil Organic Carbon

In this study, SOC concentration signifies the concentration of SOC on a mass basis (g kg^{-1}), whereas SOC pool signifies the concentration of SOC on an area basis (Mg ha^{-1}), which is in accord with similar definitions given in literature (Hooker et al., 2005). Stover removal reduced total SOC concentration in the 0- to 5-cm soil depth but not in the 5- to 10-cm depth ($P < 0.01$; Fig. 1). Magnitude of stover removal effects varied depending on soil and whether the total SOC was expressed on a mass basis (g kg^{-1}) or an area basis (Mg ha^{-1}). Changes in SOC pool were not as drastic as those based on SOC concentration. These differences between pool and concentration of SOC were due to the large effects of stover removal on ρ_b at all sites ($P < 0.01$; Fig. 2). The ρ_b increased quadratically at Coshocton and Hoytville and linearly at Charleston with increase in stover removal rate. Soil ρ_b with the T0 treatment increased by approximately 10% at Coshocton, 22% at Hoytville, and 6% at Charleston, as compared with T3.75 and T5, respectively.

The SOC concentration and pool decreased with increase in rates of stover removal at all sites but Hoytville where only differences in concentration were significant. The SOC concentration decreased quadratically at Coshocton and Charleston and linearly at Hoytville with increase in stover removal ($P < 0.01$; Fig. 1). The SOC concentration in 0- to 5-cm depth decreased from 29.6 to 19.7 g kg^{-1} at Coshocton, 27.9 to 20.5 g kg^{-1} at Charleston, and 25.7 to 22.4 g kg^{-1} at Hoytville from T5 to T0, showing that 50% of total SOC concentration was lost at Coshocton, 36% at Charleston, and 15% at Hoytville by complete removal (T0). Similarly, complete stover removal reduced SOC pool by 39% (19.0 vs. 13.7 Mg ha^{-1}) at Coshocton and by 33% (20.5 vs. 15.4 Mg ha^{-1}) at Charleston compared with the normal stover treatment (T5) ($P < 0.05$; Fig. 1).

At Coshocton, SOC concentrations between T5 and T3.75 did not differ significantly but were higher than those for T0 that had the lowest SOC concentration. Mean SOC pool at this site was in the order: T10 = T5 = T3.75 = T2.5 = T1.25 > T0, where the T0 treatment was 61% of

TABLE 2

Baseline data on soil properties from the treatment plots for the 0- to 5-cm depth by site collected just before imposition of the stover treatments in May 2004

Soil properties	Coshocton	Hoytville	South Charleston
Soil texture			
Sand, g kg^{-1}	209 ± 3	226 ± 3	222 ± 4
Silt, g kg^{-1}	638 ± 4	558 ± 2	341 ± 3
Clay, g kg^{-1}	153 ± 4	216 ± 4	437 ± 4
Bulk density, Mg m^{-3}	1.35 ± 0.03	1.29 ± 0.03	1.45 ± 0.04
Mean weight diameter of aggregates, mm	2.2 ± 0.20	1.9 ± 0.15	2.9 ± 0.30
Tensile strength of aggregates, kPa	210 ± 14	382 ± 18	220 ± 15
Total organic carbon, g kg^{-1}	30 ± 3	28 ± 2	26 ± 3

Because differences in soil properties among experimental units within each site were not significant, values are means (±SD) averaged across the six treatment plots in triplicate (n = 18).

2,4-diamine] and 2 L ha^{-1} of metolachlor at South Charleston; 3 L ha^{-1} of acetochlor [2-chloro-*N*-(ethoxymethyl)-*N*(2–ethyl-6-methylpheny) acetamide] and 2 L ha^{-1} of Cyanazine [2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino]-2-methyl-propanenitrile] at Hoytville. Liquid nitrogen (28-00-00) at 180 *N* kg ha^{-1} at Hoytville and South Charleston, whereas ammonium nitrate (34-0-0) at 152 kg *N* ha^{-1} and potash (0-0-60) at 134 kg *N* ha^{-1} at Coshocton were applied to the entire experimental area before corn planting in May 2004. After harvest, in October 2004, the new corn stover produced was chopped and redistributed immediately in the corresponding treatment plots.

Determination of Soil Properties

Bulk and core soil samples were obtained from each plot in early May 2005 before corn planting for the determination of SOC concentration, bulk density (ρ_b), water-stable aggregates (WSA), and tensile strength (TS) of aggregates. Approximately 500 g of bulk soil from 0- to 5-cm and 5- to 10-cm depths and 7.6 × 7.6-cm soil cores from the 0- to 6-cm depth were collected from each plot. Soil ρ_b was determined by the core method (Grossman and Reinsch, 2002). The bulk soil was air-dried for 72 h at 20°C, gently crushed, and passed through an 8-mm sieve and retained in a 5-mm sieve to collect aggregates of 5- to 8-mm diameter for determinations of WSA and TS. The aggregate-size fractionation for the determination of WSA was performed using the modified wet-sieving procedure (Nimmo and Perkins, 2002). Fifty grams of 5- to 8-mm aggregates was placed on top of a nest of sieves of 5-, 2-, 1-, 0.5-, and 0.25-mm mesh and saturated by capillarity for 30 min. The nest of sieves was mechanically oscillated in a water column at 30 cycles min^{-1} with an oscillation of 4 cm for 30 min using a sieving device. The amount of soil retained in each sieve was transferred to preweighed containers, oven-dried at 50°C, and weighed to compute the percentage of WSA and MWD (Nimmo and Perkins, 2002). Soil fraction <0.25 mm was obtained by collecting the sediment after decanting the water and determining the oven-dry weight. Aggregate-size fractions between 0.25 and 8 mm were grouped as macroaggregates and those <0.25 mm as microaggregates (Tisdall and Oades, 1982).

Samples for the determination of total SOC concentration of the whole soil were obtained by sieving air-dry soil to 2 mm, grinding, and then sieving to 0.25 mm. Sub-samples of each aggregate-size fraction were also ground and sieved to 0.25 mm to determine the total SOC concentration in aggregates. The total SOC in the whole soil and aggregates was determined by the dry combustion method (900°C) using a CN analyzer (Vario Max, Elementar Americas, Inc., Germany) (Nelson and Sommers, 1996). Visible corn stover and roots were removed from the whole soil and aggregates before SOC determinations. Although the SOC concentration was determined for the 0- to 5-cm and 5- to 10-cm depths, WSA and TS were determined only for the 0- to 5-cm depth.

The TS of the aggregates was determined by the crushing method (Dexter and Watts, 2001) using a simple apparatus based on a design by Horn and Dexter (1989). The TS was computed using Eq. (1) (Rogowski et al., 1968):

$$\mathrm{TS} = 0.576\left(\frac{F}{d_{agg}^{\ 2}}\right) \qquad (1)$$

where F is aggregate breaking force (N), and d_{agg} is mean aggregate diameter (m). Eq. (1) is

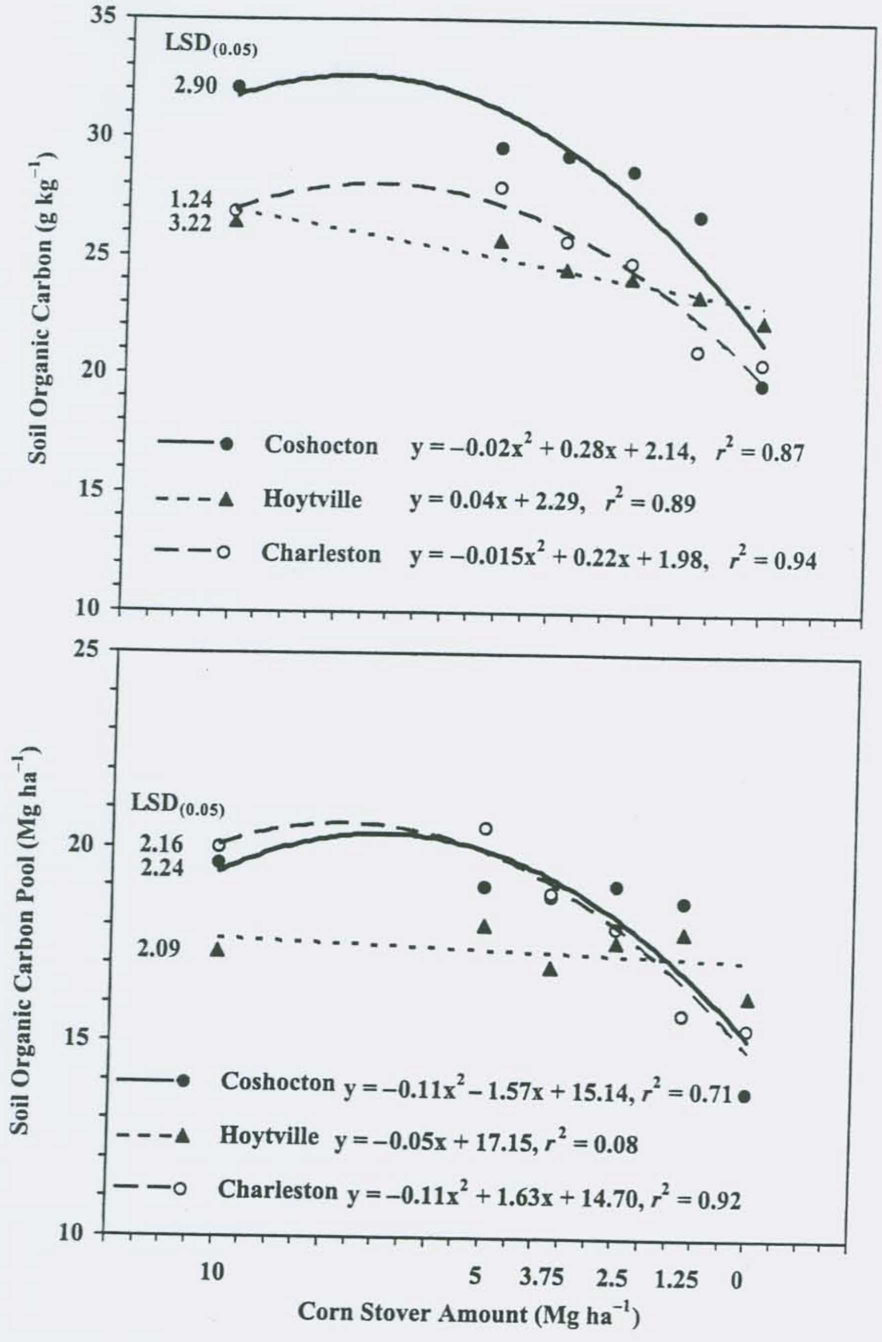

Fig. 1. Concentration and pool of SOC in the 0- to 5-cm soil depth under 0 (T0), 1.25 (T1.25), 2.50 (T2.5), 3.75 (T3.75), 5.00 (T5), and 10.00 (T10) Mg ha^{-1} of stover in NT continuous systems at Coshocton, Hoytville, and Charleston in Ohio. Because changes in SOC among treatments for the 5- to 10-cm depth were not significant, data for this depth are not reported. The highest rate of stover (10 Mg ha^{-1}) is double the normal stover rate (5 Mg ha^{-1}).

that of the other treatments. At Charleston, the SOC concentration was in the order: T10 = T5 = T3.75 = T2.5 > T1.25 = T0, where SOC concentration for the treatments >T2.5 was 1.3 times greater than that for T1.25 and T0 ($P < 0.01$; Fig. 1). At the same site, T1.25 and T0 also had lower SOC pool than T3.75, T5. At Hoytville, T0 was the only treatment with significantly lower SOC concentration than T5 ($P < 0.05$). Stover addition from T5 to T10 did not increase the SOC pool or concentration ($P > 0.10$) at any site.

Macroaggregates contained 10% to 45% more SOC concentration than microaggregates across sites and treatments (Table 3). The higher SOC concentration in macroaggregates than microaggregates decreased with increase in stover removal rates at all sites but Coshocton. For a specific aggregate-size fraction, SOC

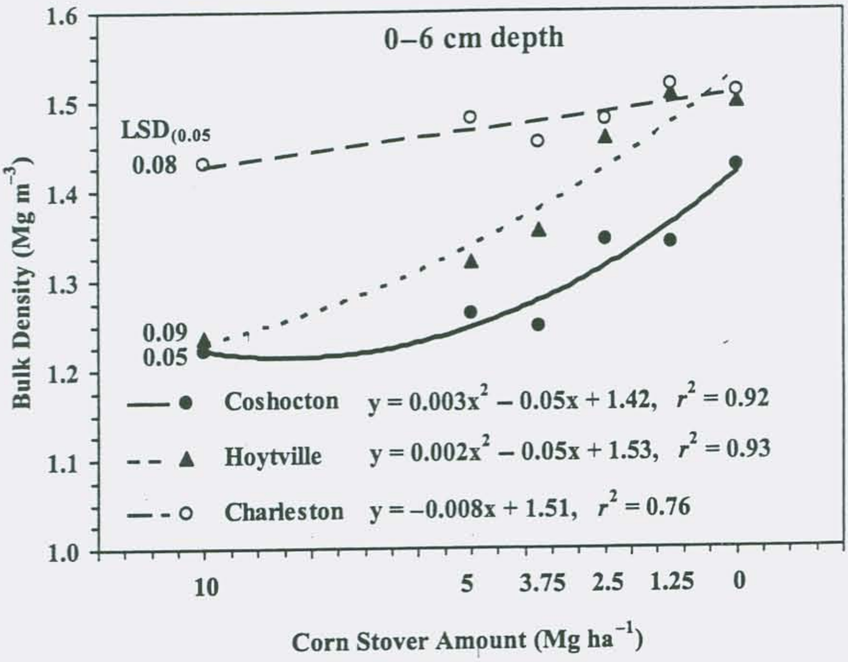

Fig. 2. Changes in bulk density in the 0- to 6-cm soil depth as a function of rates of corn stover including 0 (T0), 1.25 (T1.25), 2.50 (T2.5), 3.75 (T3.75), 5.00 (T5), and 10.00 (T10) Mg ha^{-1} of stover in NT continuous systems at Coshocton, Hoytville, and Charleston in Ohio. The highest rate of stover (10 Mg ha^{-1}) is double the normal stover rate (5 Mg ha^{-1}).

concentration in T5 and T3.75 was higher than that in T0 at Coshocton. For example, >4.75-mm macroaggregates in T0 contained 21% less SOC than T5 and T3.75 and 17% less than T2.5 and T25% at this site. Although SOC concentration decreased with increase in stover removal for each aggregate size level between 4.75 and 0.25 mm at Charleston and for the 4.75 mm aggregates at Hoytville, differences were not significant. Although not significant, microaggregates (<0.25 mm) under T0 had relatively higher SOC concentration than those under T3.75 and T5 at Charleston and Hoytville.

Stability of Aggregates

The MWD and WSA within the 0- to 5-cm soil depth are presented in Fig. 3 and Table 4, respectively. The MWD decreased in direct proportion to the increase in stover removal ($P < 0.01$), and it followed a simple linear response ($r^2 > 0.85$) at all sites but Charleston. At this site, the abrupt decrease in MWD between T5 (2.99 mm) and T3.75 (1.94 mm) was an outlier from an otherwise linear decline of MWD with increase in stover removal (Fig. 3). These data from Charleston suggest that stover removal at rates as low as 1.25 Mg ha^{-1} (25%) can significantly reduce the MWD of aggregates. The largest differences in MWD were mainly due to complete stover removal (T0). At Coshocton, MWD for T2.5, T3.75, and T5 was 1.4 times greater than that for T0. At Hoytville, the MWD for T0 was half of that for T5.

Stover removal also affected the distribution of WSA ($P < 0.01$; Table 4). It particularly influenced the distribution of >4.57-mm macroaggregates and <0.25-mm microaggregates. Compared to T5, T0 reduced >4.75-mm macroaggregates 1.4-fold at Hoytville and 2.5-fold at Charleston. At Coshocton, WSA in T0 was not different from that in T5. Stover removal effect on microaggregation was the opposite of that on macroagregation. Amount of <0.25-mm microaggregates generally increased with increase in rate of stover removal. At Coshocton, T0 and T1.25 increased microaggregates by approximately 86% relative to T5. At Hoytville, microaggregates in T0 were 1.3 times more than those in T1.25 through T5. At Charleston, stover removal at rates as low as 1.25 Mg ha^{-1} caused a 48% decrease in >4.75-mm macroaggregates compared with T5. Adding the amount of stover by 5 Mg ha^{-1} from T5 to T10 increased significantly the percentage of >4.75-mm macroaggregates except at Charleston. The T10 increased >4.75-mm macroaggregates by 33% at Coshocton and 48% at Hoytville compared with the normal stover treatment (T5).

TABLE 3

SOC distribution with aggregate size as influenced by six levels or treatments (TRT) of corn stover for the study sites at Coshocton and Charleston in Ohio

Rates of stover, Mg ha^{-1}	TRT	Aggregate size, mm						$LSD_{0.05}$
		>4.75	4.75-2	2-1	1-0.5	0.5-0.25	<0.25	
				g kg^{-1}				
				Coshocton				
10.00	T10	30.8	31.4	32.0	31.6	30.6	26.3	3.5
5.00	T5	27.9	29.2	29.6	29.8	29.9	22.0	1.2
3.75	T3.75	27.9	29.0	29.6	29.5	29.8	22.5	1.8
2.50	T2.5	27.0	27.0	28.5	29.5	29.6	23.0	1.6
1.25	T1.25	26.7	27.3	27.6	28.4	27.8	22.5	2.0
0.00	T0	22.9	24.7	25.9	25.7	26.0	17.5	3.7
	$LSD_{0.05}$	4.7	4.8	4.2	5.4	5.6	5.3	
				Hoytville				
10.00	T10	27.0	25.8	25.1	24.5	24.8	18.8	2.6
5.00	T5	25.9	25.9	24.8	24.9	24.3	17.9	1.7
3.75	T3.75	25.3	26.3	26.7	26.3	26.1	18.7	2.0
2.50	T2.5	26.5	26.0	26.2	24.9	25.9	19.6	0.9
1.25	T1.25	26.7	26.4	25.7	24.4	24.1	19.8	1.8
0.00	T0	24.6	26.4	24.8	24.5	24.2	19.3	2.2
	$LSD_{0.05}$	3.6	3.1	2.9	1.7	2.3	1.8	
				South Charleston				
10.00	T10	28.8	28.4	28.9	29.1	29.1	18.9	5.0
5.00	T5	28.4	28.1	29.5	29.9	29.7	20.5	3.2
3.75	T3.75	26.4	26.1	26.2	26.0	26.4	20.2	2.1
2.50	T2.5	25.6	25.5	25.8	25.5	25.4	19.3	1.6
1.25	T1.25	25.5	25.2	25.5	24.9	26.3	20.1	1.7
0.00	T0	24.5	24.6	24.5	24.8	26.0	23.0	3.2
	$LSD_{0.05}$	4.7	4.6	5.7	8.1	6.9	5.2	

Tensile Strength

Stover treatments impacted significantly the structural strength of surface soil aggregates ($P < 0.01$). The geometric mean TS of air-dry 5-8-mm aggregates decreased sharply with increase in rate of stover removal at all sites (Fig. 3). The TS values between T0 and T1.25 were not significantly different at any site, but they decreased abruptly with increase in removal rates from T5 to T1.25. Changes in TS values between T10 and T5 were not as drastic as those between T5 and T1.25, suggesting that stover additions above the normal applications (T5) may have lesser effect on aggregate strength than stover removal. Quadratic fits of the data in Fig. 3 showed that stover removal levels explained 93% of the variations in TS at Hoytville and 97% at Charleston. No significant linear regression fit between TS versus stover level was observed for the Coshocton site, but the TS values decreased significantly with stover removal as at other sites.

Compared to T5, TS values at T0 were 74% lower at Coshocton and 66% at Charleston and Hoytville. Soils with higher clay content had higher TS than silt loams. The TS for the clay loam soils at Hoytville exceeded that for the silt loams at Charleston and at Coshocton by 1.7 and 4.0 times, respectively.

Relationship of Soil Structural Properties With Soil Organic Carbon

Soil ρ_b was negatively correlated with SOC concentration at Coshocton and Hoytville ($P < 0.01$; Fig. 4). The SOC concentration explained 43% of the variability in ρ_b at Coshocton and 32% at Hoytville, but ρ_b versus SOC correlation at Charleston was not significant. The MWD and LogTS were positively and significantly correlated with SOC concentration, although the significance level varied among soils (Fig. 5), indicating that decrease in stover-derived SOC affected the stability and strength of aggregates. The MWD and LogTS increased linearly with increase in SOC concentration at all sites. The regression fits between SOC concentration versus MWD and LogTS were similar among the three soils. The strongest correlations were observed for the Hoytville site where changes in SOC concentration explained 48% of the

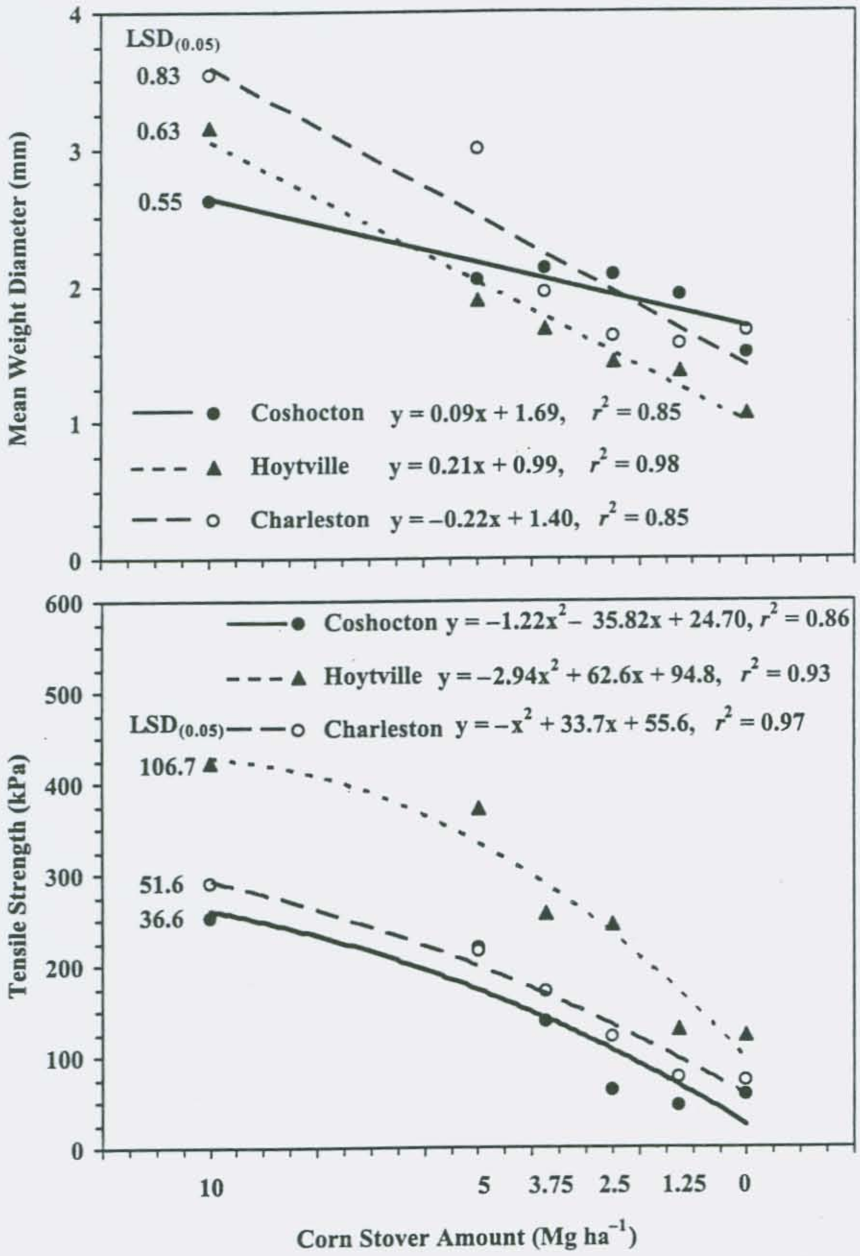

Fig. 3. MWD and geometric mean TS of aggregates in the 0- to 5-cm soil depth as a function of rates of corn stover including 0 (T0), 1.25 (T1.25), 2.50 (T2.5), 3.75 (T3.75), 5.00 (T5), and 10.00 (T10) Mg ha^{-1} of stover in NT continuous systems at Coshocton, Hoytville, and Charleston in Ohio. The highest rate of stover (10 Mg ha^{-1}) is double the normal stover rate (5 Mg ha^{-1}).

variability in MWD and 69% of LogTS. The weakest correlation between MWD and SOC concentration was observed for the Coshocton site, and the variation in SOC concentration accounted for only 19% of MWD variability ($P < 0.10$).

DISCUSSION

Soil Organic Carbon and Structural Properties

Differences in concentration and SOC pool, ρ_b, MWD, WSA, and TS among stover treatments were rather surprising. Despite the short period of stover removal, changes in the selected soil properties were significant in the 0- to 5-cm soil depth. The significant reduction in SOC pool with stover removal is attributed to the decline in stover-derived SOC. The SOC pool changes were positive (gains) when stover was returned or added and negative (losses) when removed. The differences in SOC pool among sites indicate that gains and losses in SOC pool as a result of stover removal were a function of site-specific characteristics. The little or no

TABLE 4

Distribution of water-stable aggregates (%) by aggregate size as a function of six treatments (TRT) of corn stover at Coshocton, Hoytville, and Charleston in Ohio

Rates of corn stover, Mg ha^{-1}	TRT	Aggregate size, mm					
		>4.75	4.75-2	2-1	1-0.5	0.5-0.25	<0.25
				Coshocton			
10.0	T10	26.9	16.3	13.9	14.5	10.9	17.5
5.00	T5	18.0	13.5	16.5	18.2	14.3	19.5
3.75	T3.75	18.9	15.9	17.1	12.7	7.9	27.5
2.50	T2.5	19.4	14.9	12.7	14.8	10.8	27.4
1.25	T1.25	16.7	14.9	12.1	13.4	8.6	34.3
0.00	T0	12.5	10.4	12.1	16.1	14.5	34.4
	$LSD_{0.05}$	11.4	7.4	9.8	3.7	6.1	12.9
				Hoytville			
10.00	T10	38.4	13.5	9.8	9.9	8.6	19.8
5.00	T5	20.0	10.2	9.8	12.7	12.1	35.2
3.75	T3.75	14.2	13.1	11.4	15.9	12.7	32.7
2.50	T2.5	10.7	11.2	12.8	17.2	14.5	33.6
1.25	T1.25	9.4	11.4	12.8	17.7	16.2	32.5
0.00	T0	7.7	7.5	9.5	14.7	16.5	44.1
	$LSD_{0.05}$	10.7	3.9	4.1	4.9	3.1	8.2
				South Charleston			
10.00	T10	45.5	12.8	7.1	9.4	9.1	16.1
5.00	T5	35.6	14.0	9.4	11.8	8.0	21.2
3.75	T3.75	18.5	13.3	10.7	13.8	13.6	30.1
2.50	T2.5	13.7	12.7	11.0	13.8	15.6	33.2
1.25	T1.25	13.1	10.7	12.2	17.9	14.7	31.4
0.00	T0	13.4	11.8	13.9	20.2	14.3	26.4
	$LSD_{0.05}$	11.8	5.4	4.5	5.4	3.7	10.1

effect of stover removal on SOC pool at Hoytville suggests that clay loam soils were less prone to short-term changes in SOC compared with silt loams. Rate of corn stover decomposition in clay loam soils is often slower than that in coarse-textured soils (Liang et al., 1998). One-year data for clay soils imply that removing stover as biofuel may not significantly alter the SOC pool over a short period.

Previous studies on changes in SOC pool with stover removal have reported often conflicting results. Complete stover removal (T0) from NT systems reduced corn-derived SOC pool by 35% in a 13-year study on a Waukegan silt loam (Allmaras et al., 2004) and by 30% to 39% in a 29-year study on Hamerly clay loam, McIntosh silt loam, and Winger silty clay loam (Wilts et al., 2004). Conversely, Hooker et al. (2005) reported no significant differences in SOC pool between soils with and without stover mulch after 29 years of NT management. These contrasting results may be due to two reasons. First, changes in SOC pool by stover removal are often controlled by site-specific conditions such as soil, previous management, tillage, and climate. Results in this study corroborate the site specificity of SOC pool and illustrate the need for further soil-specific assessment of SOC dynamics. Second, SOC pool in some soils such as those studied by Hooker et al. (2005) may have reached a steady-state level, above which changes in SOC pool by stover removal would be small. The rapid SOC pool reduction in the present study suggests that stover removal lowered the equilibrium SOC levels, but the status of the SOC saturation levels for these soils should be better understood. Soils close to steady-state level may have a high buffering capacity even against higher rates of stover harvesting for biofuel production without significantly affecting the total SOC pools. Doubling the stover amount did not increase significantly the SOC pool compared with normal stover application, which contrasts with the results of a 10-year NT corn by Karlen et al. (1994), who reported that doubling stover cover increased SOC pool by 33%. The short-time after stover doubling may be the reason for the no increase in SOC pool with stover addition. Conversely, results of

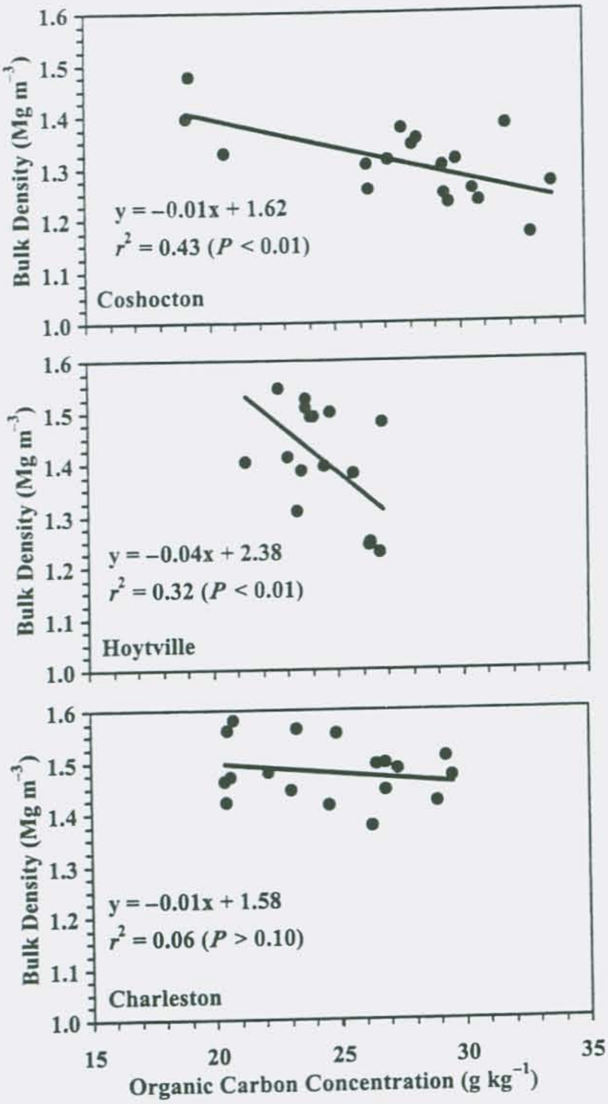

Fig. 4. Relationship of bulk density with SOC concentration as affected by corn stover management under NT continuous systems at Coshocton, Hoytville, and Charleston in Ohio.

rapid decrease in SOC pool with stover removal in silt loams indicate that removal has a larger impact on SOC pool than addition. The higher SOC concentration in macroaggregates than in microaggregates is in accord with the data from Ohio by Puget et al. (2005), who observed that macroaggregates had 15% to 35% more SOC concentration than microaggregates in NT soils at Coshocton. Macroaggregates probably encapsulated recent plant debris or labile organic matter unlike microaggregates which are mainly stabilized with highly processed and recalcitrant organic substances (Tisdall and Oades, 1982).

Decrease in aggregate stability within 1 year of complete (T0) and partial (T.125, T2.5, and T3.75) stover removal is attributed to the absence of the beneficial effects of (1) undecomposed mulch cover remaining on the soil surface and (2) decomposed stover materials. Soils without or with reduced stover cover (<2.5 Mg ha^{-1}) were likely prone to rapid dispersion of surface soil aggregates to primary particles by three possible mechanisms: (1) aggregate detachment by raindrop impact and surface runoff flow, (2) rapid wetting and drying cycles, and (3) abrupt freezing and thawing. Field observations indicated that stover-free or unmulched soils underwent visible breakdown of surface aggregates followed by deposition of detached particles as sediment. Stover decay materials provide binding agents and accentuate microbial activity necessary for enmeshing soil particles and stabilizing the intra-aggregate contacts (Johnson et al., 2004). Substances derived from decomposition of corn stover are rich in polysaccharides and phenolic lignin compounds and stabilize soil aggregates (Johnson et al., 2004). In the U.S. Corn Belt region, Morachan et al. (1972) and Karlen et al. (1994) reported that complete stover removal (T0) from NT corn reduced WSA by 10% to 30%. Similarly, Johnson et al. (2004) observed in a laboratory study that soils with no corn stover mulch had significantly lower WSA than those receiving 4.3 Mg ha^{-1} of stover.

As with MWD, the large decrease in TS with increase in stover removal was probably due to the lack of stover-derived organic materials, which act as cementing agents to strengthen the interparticle bonding of aggregates during air-drying (Hadas et al., 1994). Strong bonding of organic substances with clay particles upon soil drying is a major mechanism for increasing the TS of surface aggregates in clay and silt loams (Imhoff et al., 2002). Similar results were reported by Hadas et al. (1994), who observed that the TS of aggregates without cotton residue was rapidly reduced compared with that of aggregates from treatments receiving 4 Mg ha^{-1} of residue. Published studies comparing specifically the stover removal effects on TS under NT systems are, however, unavailable to directly compare with the findings of the present study.

The magnitude of changes in SOC pool, MWD, WSA, and TS differed among soils. The clay loam (437 g kg^{-1} clay) at Hoytville had higher MWD, macroaggregation, and TS than the silt loam (216 g kg^{-1} clay) at Charleston and (153 g kg^{-1} clay) at Coshocton, but the SOC pool at Hoytville did not change significantly with stover removal in 1 year. The higher aggregate stability and strength with increase in clay content were in accord with other studies

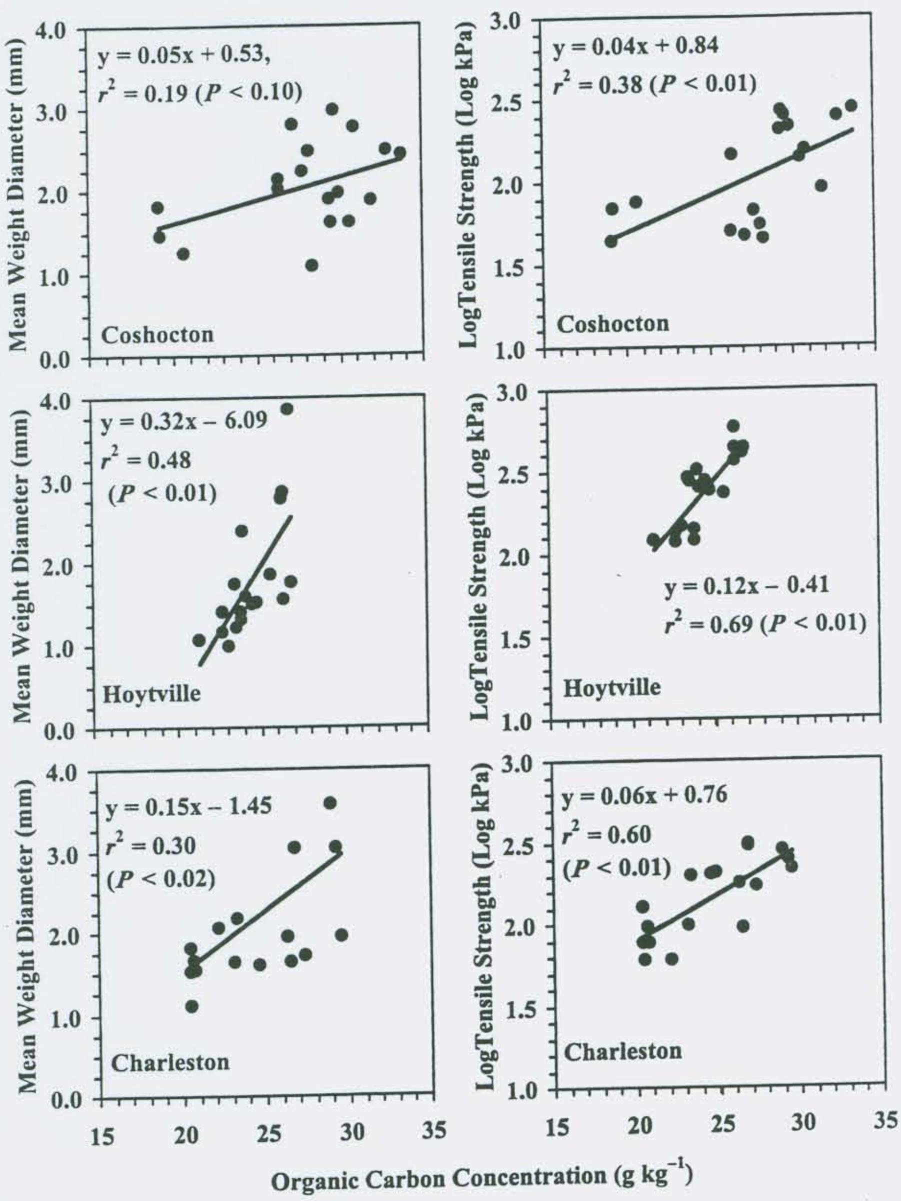

Fig. 5. Relationship of MWD and log-transformed TS of aggregates with SOC concentration as affected by corn stover management under NT continuous systems at Coshocton, Hoytville, and Charleston in Ohio.

(Imhoff et al., 2002). Upon soil drying, clay particles increase contact points and cohesion forces within the soil matrix by bridging and cementing silt and sand particles (Imhoff et al., 2002). These variations in the effects of stover removal as a result of the differences in soil intrinsic properties (e.g., texture) highlight the importance of conducting site-specific studies to determine local threshold levels of stover removal.

Differences in SOC pool, ρ_b, MWD, WSA, and TS among experimental units within each site at the start of the experiment (May 2004) were not significant ($P > 0.10$; Table 2), which is most likely explained by the uniformity of the soil and the small size of the total experimental area (11 × 18 m). Thus, the rapid and significant changes in SOC pool, ρ_b, MWD, WSA, and TS observed 1 year after stover removal or addition (May 2005) are directly attributed to the stover treatment effects. Variations in prior cropping systems among sites may not be a major factor in assessing relative differences among stover treatments within each site, as differences in SOC concentration within and among sites were nonsignificant (Table 2). Soil-specific characteristics such as texture may have, however, had a significant influence on the magnitude of stover treatment effects on the measured soil properties more than those of previous cropping systems (Liang et al., 1998). For example, as discussed earlier, changes in SOC pool due to stover removal were significant in silt loam but not in clay loam soils, suggesting inconsistencies in stover decomposition among soils.

Relationships Among Soil Properties

The significant negative SOC versus ρ_b correlation at Coshocton and Hoytville sites indicates that decrease in stover-derived SOC and raindrop impact on bare soil increased ρ_b. The high SOC concentration improves soil structure, promotes macroporosity, and reduces ρ_b (Soane, 1990). The significant positive correlation between MWD and SOC indicates that wet aggregates with high SOC concentration were more resistant to dispersion and slaking than those with low concentration. Loss of SOC accelerated particularly the destruction of >4.75-mm macroaggregates in unmulched soils. Aggregate-bound SOC moderates the water entry into the aggregates, which reduces air entrapment and pressure buildup within aggregates (Zaher et al., 2005). There is a mutual interrelationship between SOC concentration and aggregation (Bossuyt et al., 2005). The SOC-enriched organic materials are responsible for soil aggregate formation and stabilization by providing transient, temporary, and permanent organic binding agents (Tisdall and Oades, 1982). Soil aggregates, in turn, store and prevent SOC from rapid decomposition.

Similarly, the positive correlation between LogTS versus SOC concentration implies that decrease in SOC levels with increase in stover removal rate resulted in lower LogTS. The SOC stabilizes and strengthens aggregates by filling the intra-aggregate micropores and altering the nature of bonding of soil particles (Hadas et al., 1994). In accord with the present study, Imhoff et al. (2002) reported that LogTS of air-dry aggregates decreased linearly as the SOC concentration decreased in clay and silt loams. Stover removal reduces inward transfer of stover-derived humic substances, altering the cohesiveness among soil particles and weakening the bonds during drying. Slowly decomposing stover mulch cover in association with fungal hyphae and bacterial secretions enmesh soil particles into microaggregates (<250 μm) followed by the formation of stable and strong macroaggregates (>250 μm) (Tisdall and Oades, 1982). The contribution of soil macroorganisms and microorganisms feeding on corn stover to soil aggregation has been widely documented (e.g., Bossuyt et al., 2005).

The low stability of wet aggregates with increase in stover removal mirrored the low TS of air-dry aggregates. Despite having lower ρ_b and higher SOC concentration, mulched soils had stronger dry aggregates compared with unmulched soils. The lower ρ_b of mulched soils is attributed to macroporosity or inter-aggregate spaces rather than to the strength of individual soil aggregates (Ekwue, 1990; Munkholm and Kay, 2002).The positive relationship of SOC with MWD (Rhoton et al., 2002) and LogTS (Rahimi et al., 2000) has also been widely reported. The positive LogTS versus SOC correlation in this study contrasts, however, with that observed by Zhang (1994) and Watts and Dexter (1997) in which TS of air-dry aggregates increased significantly with decrease in SOC concentration. These discrepancies in TS versus SOC relationships among soils may be explained by differences in parent material (Watts and Dexter, 1997), clay content and mineralogy (Imhoff et al., 2002), organic matter type and nature (Ekwue, 1990), soil porosity (Zhang, 1994), and water content of aggregates (Munkholm and Kay, 2002).

CONCLUSIONS

Systematic corn stover removal induced rapid changes in SOC pool and soil structural parameters in NT continuous corn systems of three soils in the eastern U.S. Corn Belt region. Soil analyses conducted within 1 year of stover removal showed that complete removal (100%) reduced SOC pools and degraded soil structural properties. High rate of stover removal weakened soil aggregates, reduced water-stable macroaggregation, and increased microaggregation, although differences in soil specificity and management determine the magnitude of changes. Results also showed that changes in SOC and soil structural properties with stover removal depended on soil textural and drainage attributes. Changes of SOC pool due to stover removal were slower in clay soils than those in silt loams. Soil bulk density increased, and aggregate stability and strength decreased linearly with increase in losses of SOC. Further studies are needed to ascertain changes in SOC and soil structural parameters by stover removal and estimate the thresholds levels of stover removal for biofuel production.

ACKNOWLEDGMENTS

The authors express their thanks to Clarence Renk, Farm Manager at the Western Agricultural

Experiment Station, South Charleston, OH, and Matthew H. Davis, Farm Manager at the Northwestern Agricultural Experiment Station, Hoytville, OH, for their help with the establishment and management of the experimental plots. Research conducted within the Consortium for Research on Enhanced Carbon Sequestration in Terrestrial Ecosystems (CSiTE) program. CSiTE is supported by the U.S. Department of Energy, Office of Science as part of the Terrestrial Carbon Sequestration program in the Office of Biological & Environmental Research.

REFERENCES

Allmaras, R. R., D. R. Linden, and C. E. Clapp. 2004. Corn-residue transformations into root and soil carbon as related to nitrogen, tillage, and stover management. Soil Sci. Soc. Am. J. 68:1366–1375.

Arshad, M. A., and R. H. Azooz. 2003. In-row residue management effects on seed-zone temperature, moisture and early growth of barley and canola in a cold semi-arid region ion northwestern Canada. Am. J. Altern. Agric. 18:129–136.

Barber, S. A. 1979. Corn residue management and soil organic matter. Agron. J. 71:625–627.

Bossuyt, H., J. Six, and P. F. Hendrix. 2005. Protection of soil carbon by microaggregates within earthworm casts. Soil Biol. Biochem. 37:251–258.

Dexter, A. R., and B. Kroesbergen. 1985. Methodology for determination of tensile strength of soil aggregates. J. Agric. Eng. Res. 31:139–147.

Dexter, A. R., and C. W. Watts. 2001. Tensile strength and friability. *In:* K. A. Smith and C. E. Mullins (eds.). Soil and Environmental Analysis: Physical Methods. Marcel Dekker, New York, pp. 405–433.

Ekwue, E. I. 1990. Organic-matter effects on soil strength properties. Soil Tillage Res. 16:289–297.

Gee, G. W., and D. Or. 2002. Particle-size analysis. *In*: J. H. Dane and G. C. Topp (eds.) Methods of Soil Analysis. Part 4. Agron. Monogr. 5. SSSA, Madison, WI, pp. 255–293.

Grossman, R. B., and T. G. Reinsch. 2002. Bulk density and linear extensibility. *In*: J. H. Dane, and G. C. Topp (eds.). Methods of Soil Analysis. Part 4. Agron. Monogr. 5. SSSA, Madison, WI, pp. 201–225.

Hadas, A., E. Rawitz, H. Etkin, and M. Margolin. 1994. Short-term variations of soil physical-properties as a function of the amount and C/N ratio of decomposing cotton residues. 1. Soil aggregation and aggregate tensile-strength. Soil Tillage Res. 32:183–198.

Hooker, B. A., T. F. Morris, R. Peters, and Z. G. Cardon. 2005. Long-term effects of tillage and corn stalk return on soil carbon dynamics. Soil Sci. Soc. Am. J. 69:188–196.

Horn, R., and A. R. Dexter. 1989. Dynamics of soil aggregation in an irrigated desert loess. Soil Tillage Res. 13:253–266.

Imhoff, S., A. P. da Silva, and A. Dexter. 2002. Factors contributing to the tensile strength and friability of Oxisols. Soil Sci. Soc. Am. J. 66:1656–1661.

Johnson, J. M. F., D. Reicosky, B. Sharratt, M. Lindstrom, W. Voorhees, and L. Carpenter-Boggs. 2004. Characterization of soil amended with the by-product of corn stover fermentation. Soil Sci. Soc. Am. J. 68:139–147.

Karlen, D. L., N. C. Wollenhaupt, D. C. Erbach, E. C. Berry, J. B. Swan, N. S. Eash, and J. L. Jordahl. 1994. Crop residue effects on soil quality following 10 years of no-till corn. Soil Tillage Res. 31:149–167.

Kim, S., and B. E. Dale. 2005. Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. Biomass Bioenergy 29:426–439.

Lal, R. 2004. Is crop residue a waste? J. Soil Water Conserv. 59:136A–139A.

Larson, W. E., C. E. Clapp, W. H. Pierre, and Y. B. Morachan. 1972. Effects of increasing amounts of organic residues on continuous corn: II. Organic carbon, nitrogen, phosphorous, and sulfur. Agron. J. 64:204–208.

Liang, B. C., E. G. Gregorich, A. F. MacKenzie, M. Schnitzer, R. P. Voroney, C. M. Monreal, and R. P. Beyaert. 1998. Retention and turnover of corn residue carbon in some eastern Canadian soils. Soil Sci. Soc. Am. J. 62:1361–1366.

Morachan, Y. B., W. C. Moldenhauer, and W. E. Larson. 1972. Effects of increasing amounts of organic residues on continuous corn: I. Yields and soil physical properties. Agron. J. 64:199–203.

Munkholm, L. J., and B. D. Kay. 2002. Effect of water regime on aggregate tensile strength, rupture energy, and friability. Soil Sci. Soc. Am. J. 66:702–709.

Nimmo, J. R., and K. S. Perkins. 2002. Aggregate stability and size distribution. *In:* J. H. Dane and G. C. Topp (eds.). Methods of Soil Analysis. Part 4. Agron. Monogr. 5. SSSA, Madison, WI, pp. 317–327.

Nelson, D. W., and L. E. Sommers. 1996. Total carbon, organic carbon, and organic matter: laboratory methods. *In:* D. L. Sparks et al. (eds.). Methods of Soil Analysis. Part 3. SSSA Book Ser. No. 5 SSSA and ASA, Madison, WI, pp. 961–1010.

Pacala, S., and R. Socolow. 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 305:968–972.

Puget, P., R. Lal, C. Izaurralde, M. Post, and L. Owens. 2005. Stock and distribution of total and corn-derived soil organic carbon in aggregate and primary particle fractions for different land use and soil management practices. Soil Sci. 170:256–279.

Rahimi, H., E. Pazira, and F. Tajik. 2000. Effect of soil organic matter, electrical conductivity and sodium adsorption ratio on tensile strength of aggregates. Soil Tillage Res. 54:145–153.

Rhoton, F. E., M. J. Shipitalo, and D. L. Lindbo. 2002. Runoff and soil loss from midwestern and southeastern US silt loam soils as affected by tillage practice and soil organic matter content. Soil Tillage Res. 66:1–11.

Rogowski, A. S., W. C. Moldenhauer, and D. Kirkham. 1968. Rupture parameters of soil aggregates. Soil Sci. Soc. Am. Proc. 32:720–724.

SAS Institute. 1999. SAS/STAT User's Guide. Version Windows 8. SAS Institute Inc., Cary, NC.

Sloneker, L. L., and W. C. Moldenhauer. 1977. Measuring the amounts of crop residue remaining after tillage. J. Soil Water Conserv. 32:231–236.

Soane, B. D. 1990. The role of organic-matter in soil compactibility—a review of some practical aspects. Soil Tillage Res. 16:179–201.

Tally, S. 2002. Making biofuel from corn stover. Biocycle 43:62.

Tisdall, J. M., and J. M. Oades. 1982. Organic matter and water stable aggregates in soils. J. Soil Sci. 33:141–163.

Watts, C. W., and A. R. Dexter. 1997. The influence of organic matter in reducing the destabilization of soil by simulated tillage. Soil Tillage Res. 42:253–275.

Wilhelm, W. W., J. M. F. Johnson, J. L. Hatfield, W. B. Voorhees, and D. R. Linden. 2004. Crop and soil productivity response to corn residue removal: a literature review. Agron. J. 96:1–17.

Wilts, A. R., D. C. Reicosky, R. R. Allmaras, and C. E. Clapp. 2004. Long-term corn residue effects: harvest alternatives, soil carbon turnover, and root-derived carbon. Soil Sci. Soc. Am. J. 68:1342–1351.

Zaher, H., J. Caron, and B. Ouaki. 2005. Modeling aggregate internal pressure evolution following immersion to quantify mechanisms of structural stability. Soil Sci. Soc. Am. J. 69:1–12.

Zhang, H. 1994. Organic matter incorporation affects mechanical properties of soil aggregates. Soil Tillage Res. 31:263–275.