Corn Stover Removal for Expanded Uses Reduces Soil Fertility and Structural Stability

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Corn (*Zea mays* L.) stover is an asset to recycle essential plant nutrients and buffer soil against natural and human perturbations. Its indiscriminate removal for industrial uses may thus adversely impact soil fertility and productivity. Research data on the impacts of stover removal are needed to establish threshold levels of stover management. Thus, this study documented the 4-yr impacts of a systematic removal of stover on selected soil fertility indicators and structural stability across three contrasting soils in Ohio under no-till (NT) management, including a Rayne silt loam, Celina silt loam, and Hoytville clay loam. Stover was removed at rates of 0, 25, 50, 75, and 100% after harvest for 4 yr. Complete stover removal reduced the total N pool by, on average, 0.82 Mg ha^{-1} in the silt loams but had no effect in the clay loam. It reduced available P by 40% and exchangeable Ca^{+2} and Mg^{+2} and the cation exchange capacity by 10% on the sloping silt loam. Exchangeable K^+ decreased by 15% on the silt loams for stover treatments ≥75% removal and by 25% under complete removal on the clay loam in the 0- to 10-cm depth. Stover removal at rates ≥25% reduced soil macroaggregates (>4.75 mm) by 40% in nearly level soils while 100% removal reduced them by 60% on the sloping soil. Available P and K^+ were predictors ($R^2 = 0.77$) of grain yield while soil organic C (SOC) and total N pools were predictors ($R^2 = 0.45$) of stover yield on the sloping silt loam. Based on the data (e.g., SOC pools) from this and previous studies, we determined that only about 25% of stover might be available for removal, and that stover removal has the most adverse impacts on sloping and erosion-prone soils.

Abbreviations: CEC, cation exchange capacity; CSL, Celina silt loam; EC, electrical conductivity; HCL, Hoytville clay loam; MWD, mean weight diameter; NT, no-till; SOC, soil organic carbon; SOM; soil organic matter; RSL, Rayne silt loam; WSA, water-stable aggregates.

Concerns about dependence on fossil fuels, increased emissions of atmospheric greenhouse gases, and, in particular, the recent steady increases in fossil fuel prices are propelling interest in producing biofuel from renewable energy sources. Among the potential biofuel feedstocks are crop residues (Graham et al., 2007), dedicated energy crops (Samson et al., 2005), and prairie grasses (Tilman et al., 2006). At present, mainly grain crops (e.g., corn) are being targeted for biofuel production. Because the use of grain crops for biofuel production may drive up prices and increase demands for food (Scharlemann and Laurance, 2008), attention will probably soon shift from grain-based ethanol to cellulosic ethanol involving cellulose-rich biomass feedstocks (e.g., crop residues). One of the main feedstocks for lignocellulosic ethanol, specifically in the U.S. Corn Belt region, is corn stover, the aboveground biomass left after the grain harvest, because of its easy availability and high cellulosic content. At present, corn stover harvesting as biofuel feedstocks is not common, but there is a strong interest in using lignocellulosic biomass for ethanol production in the near future (Graham et al., 2007).

A high rate of corn stover removal not only for producing biofuel but also for other uses (e.g., animal feed and bedding) can, however, adversely impact agronomic productivity and soil and environmental quality (Salinas-Garcia et al., 2001; Blanco-Canqui and Lal, 2007; Wilhelm et al., 2007; Lal, 2008). Indeed, the main concern in relation to agronomic production is the severity of the long-term impact of stover removal on soil fertility and productivity. Corn stover is an important reservoir of several elements (e.g., C, K, Ca, Mg, N, and P). Thus, its return to the soil after harvest is essential to element recycling and sustaining grain and biomass yields. It is thus hypothesized that long-term stover harvesting for expanded uses may reduce nutrient pools in the long term regardless of the soil type and ecosystem. Fixen (2007) estimated that removal of stover at rates of 40% would reduce the soil N content by 20%, P by 14%, and K by 110% in the U.S. Corn Belt region. High stover removal for other uses also reduces soil fertility. In a subhumid tropical region in Mexico, SOC, total N, and extractable P decreased when stover was removed for livestock feeding at rates of 0, 33, 66, and 100% from NT clay and silty clay soils (Salinas-Garcia et al., 2001). Historically, as much as 50 to 70% of the SOC pool has been lost from agricultural soils through the use of conventional tillage practices and removal or burning of crop residues (Wilhelm et al., 2007). The magnitude of changes in nutrient pools resulting from stover removal probably depends on the amount of stover removed and site-specific characteristics. Karlen et al. (1984) observed no significant differences in extractable P, K, Ca, Mg, Mn, or Zn in plots with stover removal rates of 0, 66, and 90% in a sandy loam soil. In another study, Karlen et al.

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(1994) observed a large decrease in SOC and total N concentrations due to complete stover removal in a silt loam soil. A recent study by Blanco-Canqui and Lal (2007) showed that systematic stover removal decreased SOC concentration, increased the soil's susceptibility to compaction, and reduced crop yields, but the effects were soil specific. Studies along these lines specifically assessing stover-removal-induced changes in nutrient pools are few (Larson et al., 1972; Salinas-Garcia et al., 2001) and are needed to formulate decision support systems.

Current estimates of threshold removal rates of stover for biofuel production, which suggest that 30 to 50% (Nelson, 2002; Kim and Dale, 2004; Graham et al., 2007) of crop residues can be removed, are principally based on the requirements to control soil erosion below the tolerable limit (*T* value) but not specifically on the need to maintain soil fertility and productivity. Wilhelm et al. (2007) determined that the amount of stover required to maintain SOC pools is greater than that required to control soil erosion. Thus, it is hypothesized that the amount of stover required to maintain essential nutrients and other soil chemical and physical properties is also higher than that required to control erosion.

While many have reviewed the agronomic, soil, and environmental implications of the use of crop residues as biofuel (Mann et al., 2002; Wilhelm et al., 2007) and examined the impacts of complete stover removal on soil organic matter (SOM) content (Karlen et al., 1994; Hooker et al., 2005), seldom have the effects of partial stover removal (Karlen et al., 1984; Salinas-Garcia et al., 2001) on soil fertility and structural properties been addressed under different soil types for NT management. Such information is crucial for determining the threshold level of stover needed to maintain soil fertility. Data on the impacts of stover removal on soil structural properties such as aggregate stability are not well documented. Karlen et al. (1994) observed no impacts of complete stover removal on aggregate stability in two silt loam soils in Iowa. In contrast, Blanco-Canqui et al. (2006) observed a rapid decrease in aggregate stability following 1 yr of stover removal for the soils in Ohio that were also investigated in the present study. Further characterization of soil structural stability is thus warranted under variable rates of stover management.

This study documented and quantified the 4-yr impacts of systematic removal of stover from continuous NT corn systems on selected essential plant nutrients and chemical properties, as well as soil structural stability in three soils with contrasting textural classes and topographic conditions in Ohio. This study differed from our previous studies of the effects of stover removal on soil properties and crop yields (Blanco-Canqui et al., 2006; Blanco-Canqui and Lal, 2007) because it specifically investigated the stover removal impacts on selected soil chemical properties and essential plant nutrients in addition to changes in SOC concentration and aggregate stability.

MATERIALS AND METHODS

Study Sites

This study was conducted on ongoing stover management experiments established on three soils in Ohio in 2004. The study sites were located on the North Appalachian Experimental Watersheds (NAEW) near Coshocton, the Western Agricultural Experiment Station (WAES) near South Charleston, and the Northwestern Agricultural Experiment Station (NWAES) near Hoytville in Ohio. The soils at these three sites differ in their texture, drainage, and slope. The soil at the NAEW site was a Rayne silt loam (RSL) (a fine-loamy, mixed, active, mesic Typic Hapludult) with 10% slope, while the soil at the WAES site was a Celina silt loam (CSL) (a fine, mixed, active, mesic Aquic Hapludalf) with 2% slope, and at the NWAES site the soil was a Hoytville clay loam (HCL) (a fine, illitic, mesic Mollic Epiaqualf) with <1% slope. The study site at NAEW is on a sloping watershed with unglaciated soils while the sites at WAES and NWAES are on glaciated and nearly level soils. Before establishment of the experiment in 2004, the NAEW site was under 35-yr continuous NT corn, while the WAES site was under 15 yr of a continuous NT corn–soybean [*Glycine max* (L.) Merr.] rotation and the NWAES site was under 8 yr of a continuous NT corn–soybean rotation with disking in alternate years. Further details on site description and previous management have been provided by Blanco-Canqui and Lal (2007).

Stover refers to the aboveground biomass (e.g., stalks, cobs, and leaves) left on the soil surface after corn harvest (Wilhelm et al., 2004). Five treatments in triplicate consisting of removing 0, 25, 50, 75, or 100% of the corn stover were set up in a randomized complete block design in 3- by 3-m plots. Each plot was sown to corn each year under typical NT practices in the region. The plots at NAEW received 150 kg N and 134 kg K ha^{-1} yr^{-1}, while those at WAES and NWAES received 82 and 68 kg N ha^{-1} yr^{-1}, respectively, between 2004 and 2007. The stover produced at harvest was distributed at the preset levels in the corresponding plot. The protocol for the stover removal was the following. The percentage (25, 50, or 75%) of the stover in each plot was achieved by dividing the corresponding plot into four equal quadrants, and then removing all the stover from one quadrant for the treatment with 75% stover cover, two quadrants for the treatment with 50% cover, and three quadrants for treatment with 25% cover. The stover remaining in each plot after removal was uniformly redistributed across the whole plot. The treatment with 0% stover cover involved removing the entire stover cover, leaving the soil completely bare.

Data Collection and Analyses

A 1-kg bulk soil sample was collected from each treatment plot at each site in October 2007 after harvest from the 0- to 10- and 10- to 20-cm depth increments for determination of the following soil fertility indicators: total SOC, total N, available P, K^+, Ca^{+2}, and Mg^{+2}, cation exchange capacity (CEC), pH, and electrical conductivity (EC). Soil samples were air dried for 48 h at 20°C. The SOC and total N concentrations were determined by dry combustion (900°C) using a CN analyzer (Vario Max, Elementar Analysensysteme, Hanau, Germany; Nelson and Sommers, 1996) on air-dried and ball-milled samples passed through a 0.25-mm sieve. Soil cores were collected in triplicate using metal sleeves, 5.4 cm in diam. by 6 cm deep, from each site and within each plot using a hammer-driven sampler from the two depth intervals for determination of bulk density by the core method (Grossman and Reinsch, 2002), which was used to calculate the total SOC and N pools (Mg ha^{-1}). In this study, the SOC pool (Mg ha^{-1}) represents the total pool size because we did not partition the SOC into the different pools (e.g., labile or stable). The C/N ratio was computed by dividing the SOC by the N concentration (g kg^{-1}). The Bray-P extraction method (Bray-1 P; Kuo, 1996) was used for the determination of available P while the 1 mol L^{-1} NH_4OAc soil extraction method was used for the determination of exchangeable K^+, Ca^{+2}, and Mg^{+2} (Helmke and Sparks, 1996). Soil pH was determined in water using a 1:1 soil/water mixture (Thomas, 1996), and EC was measured using 1:5 soil/water mixtures (Rhoades, 1996). The CEC was expressed on an air-dried soil basis ($cmol_c$ kg^{-1}) (Rhoades, 1996).

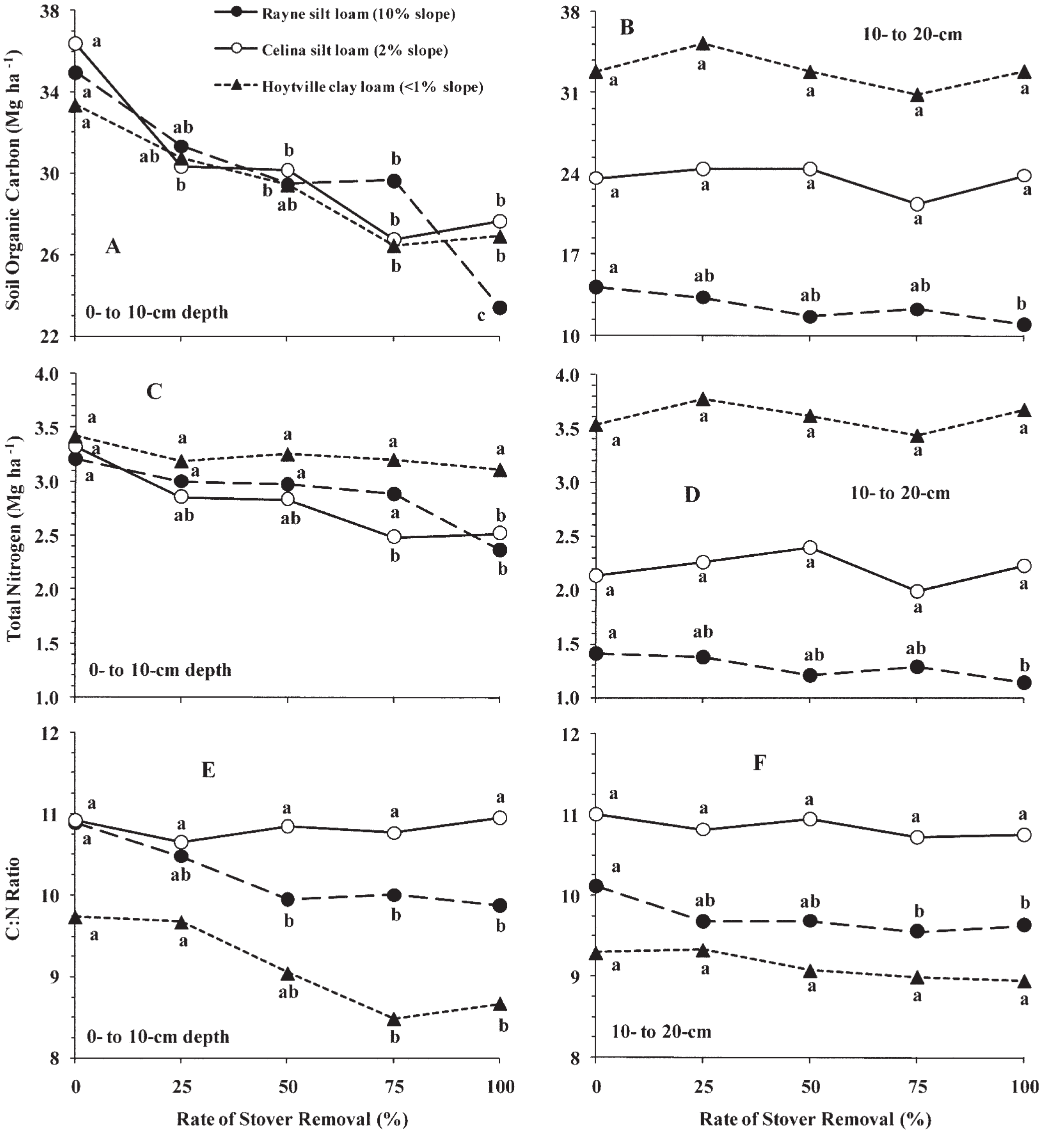

Fig. 1. Changes in soil organic C, total N, and the C/N ratio by soil depth (0–10 and 10–20 cm) due to stover management under three contrasting no-till soils in Ohio. Means followed by the same letter within the same soil are not significantly different.

The water-stable aggregates (WSA) were determined by the wet-sieving procedure (Nimmo and Perkins, 2002), using a nest of five sieves of 4.75-, 2-, 1-, 0.5-, and 0.25-mm mesh placed in descending order inside a water tank. Fifty grams of air-dry aggregates (4.75- and 8-mm diam.) were placed on the uppermost sieve of the nest, saturated by capillarity for 30 min, and oscillated in water at 30 cycles min^{-1} with an amplitude of 4 cm for 30 min using a mechanical sieving device. Aggregates remaining on each sieve were transferred to beakers, dried at 105°C, and weighed to compute the percentage of WSA and the mean weight diameter (MWD). The two related aggregate stability parameters, WSA and MWD, were assessed to better understand aggregate stability in that WSA provides the weight for each aggregate size fraction whereas MWD provides an overall mean, dominated by the weight of larger aggregate sizes. The soil fraction <0.25 mm was calculated as the difference between the initial air-dry aggregate amount and the sum of the amounts retained in each sieve. Aggregate size fractions between 0.25 and 8 mm were classified as macroaggregates and those <0.25 mm as microaggregates (Tisdall and Oades, 1982). Corn grain and stover yields were determined on the center two rows of each plot in October 2007, and the results are reported at a grain moisture content of 155 g kg^{-1}.

Statistical Analyses

A one-way ANOVA model was used to test whether differences in soil chemical properties, WAS, and the MWD of aggregates by soil type were significant. Pearson's correlation coefficients among soil properties and crop yields were computed for each study site. Stepwise multiple regression analyses were performed to develop pedotransfer functions or predictive equations for estimating grain and stover yields by soil type. All statistical analyses were conducted using SAS (SAS Institute, 2008). Fisher's protected LSD test was used to determine any differences among stover treatments. Statistical differences are reported at the 0.05 probability level, unless otherwise indicated.

RESULTS

Total Nitrogen

Stover removal reduced the total SOC and N concentrations after 4 yr of the experiment, but the magnitude of the reductions depended on the stover removal rate and the soil type (Fig. 1, Table 1). Because the trends of changes in SOC concentration due to stover removal did not differ from those reported by Blanco-Canqui and Lal (2007) for the same exper-

Table 1. Fertility indicators and related chemical properties for three contrasting soils under five levels of stover management in Ohio (SOC = soil organic carbon; EC = electrical conductivity; CEC = cation exchange capacity).

Soil and slope	Rate of stover removal	Total N	SOC	pH	EC	Ca^{+2}	Mg^{+2}	CEC
	%	g kg^{-1}			dS m^{-1}	mg kg^{-1}		$cmol_c$ kg^{-1}
				0- to 10-cm depth				
Rayne silt loam, 10%	0	2.5 a	27.1 a	7.06 a	0.25 b	1663 a	525 a	13.6 a
	25	2.4 a	24.9 a	7.04 a	0.25 b	1541 ab	475 ab	12.6 ab
	50	2.3 ab	23.0 ab	7.07 a	0.35 a	1573 ab	482 ab	12.8 ab
	75	2.3 ab	23.3 ab	7.12 a	0.34 a	1590 ab	490 ab	12.9 ab
	100	1.9 b	18.9 b	7.15 a	0.36 a	1513 b	457 b	12.2 b
Celina silt loam, 2%	0	2.6 a	28.0 a	6.70 a	0.16 a	2208 a	585 a	18.4 a
	25	2.3 ab	24.1 ab	6.76 a	0.17 a	2145 a	555 a	17.3 a
	50	2.2 ab	25.1 ab	7.26 a	0.15 a	2253 a	566 a	17.2 a
	75	1.9 ab	20.4 b	7.01 a	0.13 a	2003 a	524 a	15.7 a
	100	2.0 b	21.4 b	7.16 a	0.13 a	2195 a	556 a	17.2 a
Hoytville clay loam, <1%	0	2.7 a	26.8 a	5.63 a	0.15 b	2328 a	413 a	21.6 a
	25	2.7 a	25.7 a	5.52 ab	0.17 b	2251 a	411 a	21.9 a
	50	2.7 a	24.0 ab	5.73 ab	0.25 b	2316 a	415 a	20.6 ab
	75	3.2 a	22.8 ab	5.76 ab	0.47 a	2316 a	391 a	18.4 ab
	100	2.4 a	21.2 b	5.96 b	0.40 a	2187 a	390 a	20.1 b
				10- to 20-cm depth				
Rayne silt loam, 10%	0	1.1 a	11.2 a	7.35 b	0.20 a	1029 a	312 a	8.5 a
	25	1.0 ab	10.1 ab	7.30 b	0.19 a	1030 a	302 a	8.2 a
	50	0.9 ab	8.9 ab	7.36 b	0.21 a	969 a	293 a	7.8 a
	75	1.0 ab	9.1 b	7.35 b	0.22 a	971 a	296 a	7.8 a
	100	0.9 b	8.2 b	7.49 a	0.23 a	951 a	290 a	7.8 a
Celina silt loam, 2%	0	1.5 a	17.1 a	7.38 a	0.12 a	2373 a	577 a	17.2 a
	25	1.6 a	17.9 a	7.24 a	0.12 a	2283 a	581 a	16.7 a
	50	1.7 a	19.9 a	7.63 a	0.13 a	2360 a	556 a	16.9 a
	75	1.4 a	15.3 a	7.54 a	0.11 a	2225 a	563 a	16.1 a
	100	1.7 a	18.6 a	7.48 a	0.11 a	2455 a	568 a	17.4 a
Hoytville clay loam, <1%	0	2.3 a	21.6 a	6.00 a	0.14 a	2653 b	418 a	22.7 a
	25	2.3 a	22.0 a	5.85 a	0.15 a	2644 b	437 a	23.1 a
	50	2.3 a	20.5 a	6.09 a	0.16 a	2780 ab	450 a	22.3 a
	75	2.1 a	19.2 a	6.10 a	0.17 a	2928 a	430 a	23.9 a
	100	2.2 a	20.0 a	6.01 a	0.17 a	2660 ab	425 a	22.6 a

iment after 2½ yr, discussions in this study focused on total N pool and other soil fertility indicators. Stover removal reduced the total N pool, but reductions were significant only for the silt loams (RSL and CSL; Fig. 1). Stover removal reduced the total N pool in RSL in both depth intervals, but in CSL, reduction in the N pool was significant only in the 0- to 10-cm depth. Complete stover removal reduced the total N pool by 26% (0.84 Mg ha^{-1}) in RSL and by 25% (0.80 Mg ha^{-1}) in CSL. In the 10- to 20-cm depth, on average, 19% (0.27 Mg ha^{-1}) of the total N pool was lost in the RSL by 100% stover removal. The impacts of stover removal on total N on a mass basis were only significant when the stover was completely removed from both soils (Table 1), where total N decreased by an average of 25%. The soil C/N ratio was significantly reduced in RSL and HCL but not in CSL (Fig. 1). Removal of stover at 50% in RSL and 75% in HCL reduced the C/N ratio by 10% in the 0- to 10-cm depth. In the 10- to 20-cm depth, removal of ≥75% reduced the C/N ratio by 10% in RSL.

Available Phosphorus and Exchangeable Potassium

The impacts of stover removal on the available P concentration were significant only in RSL (Fig. 2), where complete stover removal reduced available P by 40% (20 mg kg^{-1}) in the 0- to 10-cm depth. The available P concentration also decreased with increasing stover removal in CSL, but the differences were not significant due to the high variations in data. In contrast, the impacts of stover removal on K^+ were significant in all soils when the stover removal rate was ≥75% (Fig. 2). In RSL, the impacts on K^+ were significant in both depth intervals. In the 0- to 10-cm depth, 75% of stover removal reduced K^+ by 15% (57 mg kg^{-1}) in RSL and by 21% (77 mg kg^{-1}) in CSL, whereas complete stover removal reduced it by 15% in RSL and by 31% in CSL. In HCL, K^+ was reduced only by complete removal, declining by 25% (90 mg kg^{-1}). In the 10- to 20-cm depth in RSL, K^+ declined by 30% (80 mg kg^{-1}) with ≥75% stover removal.

Exchangeable Calcium and Magnesium, pH, Electrical Conductivity, and Cation Exchange Capacity

Cations Ca^{+2} and Mg^{+2} and the CEC decreased and the pH and EC increased with increasing stover removal rate in the three soils, but statistical differences were soil specific. Stover removal impacts on Ca^{+2} and Mg^{+2} in the 0- to 10-cm depth were significant only in RSL (Table 1), where complete stover removal reduced Ca^{+2} by 10% (150 mg kg^{-1}) and Mg^{+2} by

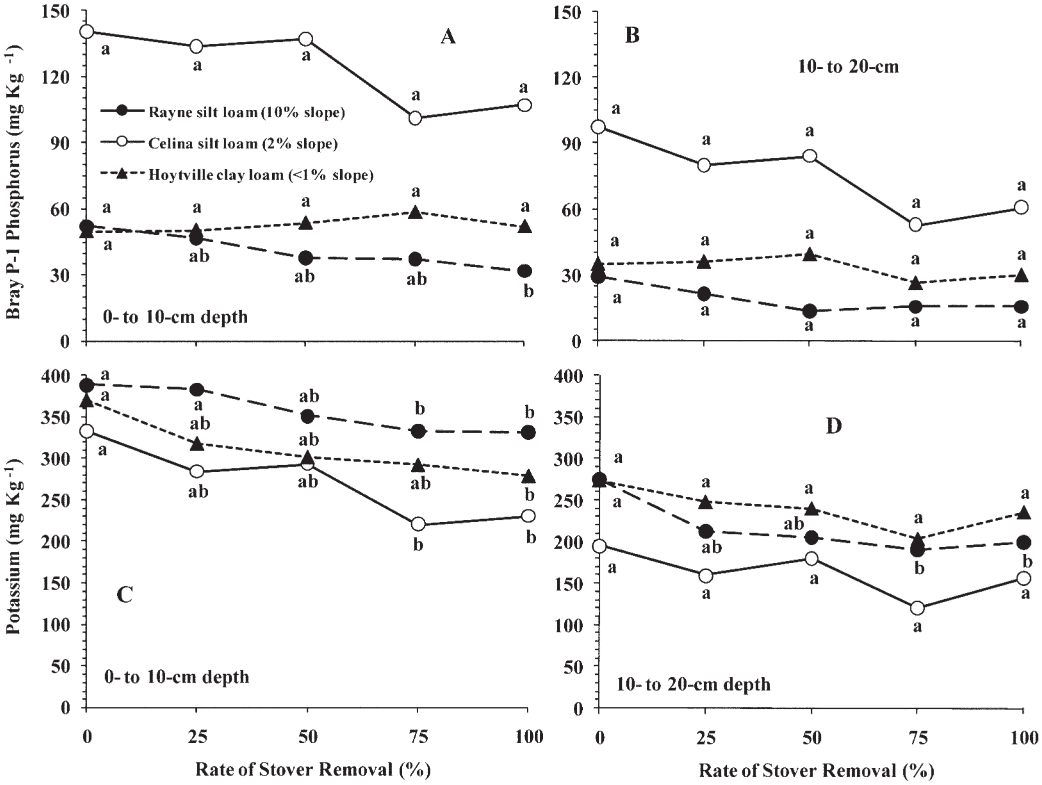

Fig. 2. Changes in available P and exchangeable K by soil depth (0–10 and 10–20 cm) due to stover management under three contrasting no-till soils in Ohio. Means followed by the same letter within the same soil are not significantly different.

13% (68 mg kg^{-1}). The impacts of stover removal on pH were small and differences were significant only in HCL, where pH in the 0- to 10-cm depth increased by 6% with 100% stover removal (Table 1). The values of EC were small but increased slightly with increasing stover removal rates in RSL and HCL, mirroring the trends in pH. Complete stover removal increased EC by 0.1 dS m^{-1} in RSL and by 0.20 dS m^{-1} in HCL. It reduced CEC by 10% (13.6 vs. 12.2 $cmol_c$ kg^{-1}) in RSL and by 7% (21.6 vs. 20.1 $cmol_c$ kg^{-1}) in HCL in the surface 0- to 10-cm depth.

Soil Aggregate Stability

The magnitude of stover removal impacts on aggregate stability for the 0- to 10- cm depth was similar to that reported by Blanco-Canqui et al. (2006) after 1 yr for the same experiments for the 0- to 5-cm soil depth. Blanco-Canqui et al. (2006) reported data on MWD only for the surface 0- to 5- cm depth, whereas, in this study, aggregate stability expressed as WSA (Fig. 3) and MWD (Fig. 4) are reported for the 0- to 10- and 10- to 20-cm depths. Stover removal reduced WSA and MWD within both soil depths in RSL and only within the 0- to 10-cm soil depth in CSL and HCL. Complete stover removal reduced the percentage of macroaggregates (>4.75 mm) by 2.7 times in RSL, 2.3 times in CSL, and 5.7 times in HCL, and doubled the proportion of microaggregates (<0.25 mm) in all soils. It reduced MWD by 1.8 in RSL and CSL and by three in HCL (Fig. 4).

The data in Fig. 3 show a reversal of the relationship between the WSA percentage and aggregate size with stover removal across all soils, particularly in the 0- to 10-cm depth. The WSA decreased systematically with decreasing aggregate size under the 0% stover removal treatment, whereas it increased with decreasing aggregate size under complete stover removal. The influence of stover removal on WSA for macroaggregates between 4.75 and 0.25 mm was less than that for >4.75-mm macroaggregates and <0.25-mm microaggregates. In RSL, complete stover removal increased the amount of aggregates between 1.00 and 0.5 mm but not in the other soils. It also increased the WSA percentage between 0.5 and 0.25 mm in RSL and HCL. In RSL, stover removal at rates up to 75% did not affect the WSA and MWD. On the contrary, in CSL and HCL, removal at rates as low as 25% reduced the percentage of >4.75-mm macroaggregates, increased the <0.25-mm microaggregates, and reduced the MWD.

Grain and Stover Yields

Mean grain and stover yields for the 4 yr of experiment are reported in Table 2. Stover removal reduced the corn grain yield in all years except the first year (2004), but impacts were significant only in the RSL site. Averaged across years, grain yield decreased by 1.4 Mg ha^{-1} with 50% stover removal and by 3.1 Mg ha^{-1} with ≥75% stover removal in RSL. The decrease in stover yield was generally smaller than that in grain yield. In 2005, stover yield was reduced by 2.2 Mg ha^{-1} with 50% stover removal and by 3.9 Mg ha^{-1} with ≥75% stover removal. In 2006 and 2007, however, stover yield decreased only with 100% stover removal by 1.4 Mg ha^{-1}. Because changes in stover removal impacts on corn yield after 4 yr of the experiment were similar to those discussed earlier by Blanco-Canqui and Lal (2007) after 2½ yr of removal, this study primarily focused on the relationships between corn yield and soil fertility indicators.

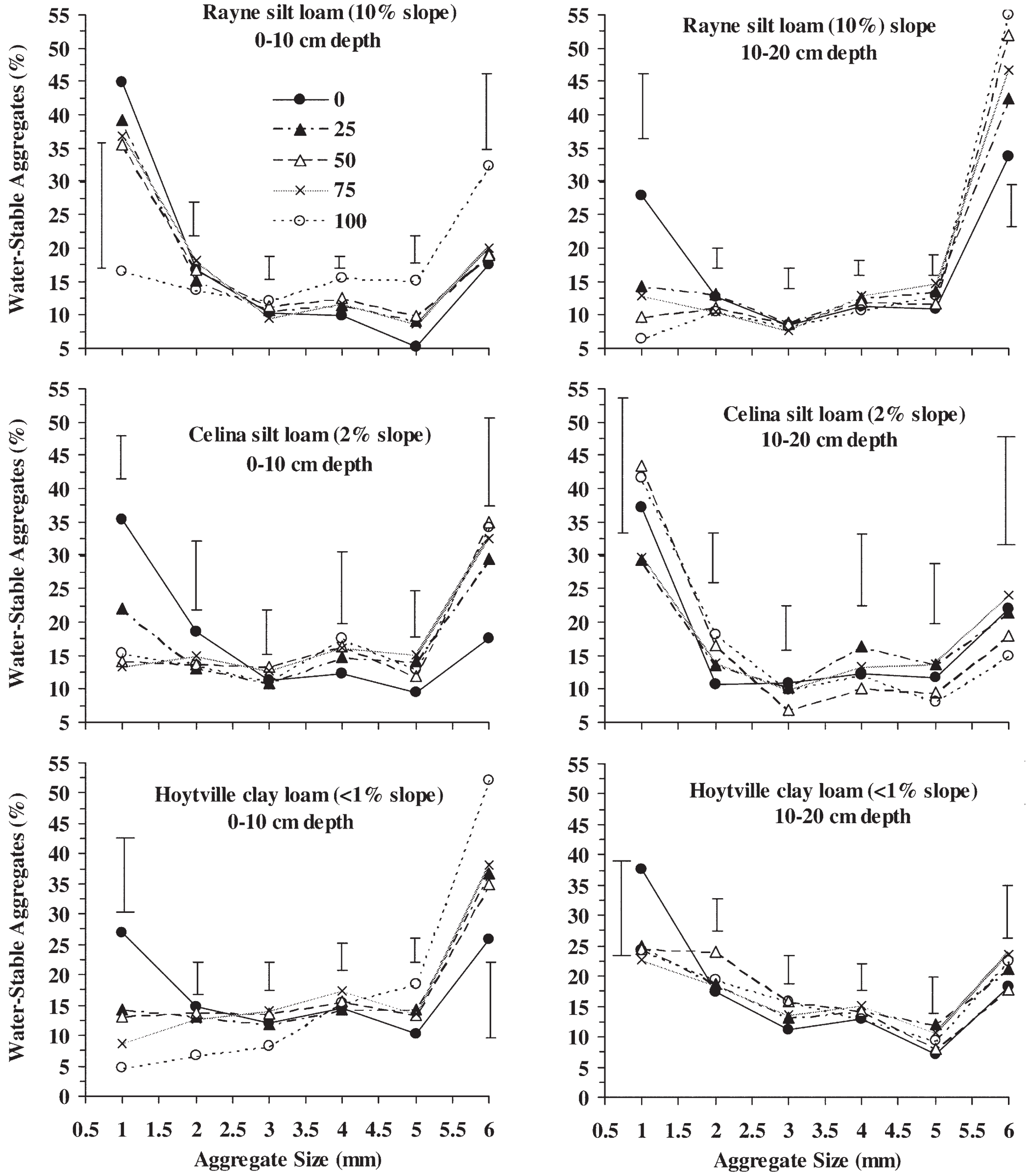

Fig. 3. Size distribution of aggregates as affected by five stover treatments for the 0- to 10-and 10- to 20-cm soil depths under three contrasting soils. The error bars are the LSD values comparing the stover treatment effects by aggregate size class.

Interrelationship among Crop Yields, Nutrient Pools, and Soil Aggregate Stability

Correlations among crop yields and soil fertility indicators were soil specific (Table 3). The grain yield was significantly correlated with SOC concentration, available P, K^+, Ca^{+2}, and Mg^{+2}, and CEC in RSL but not in CSL or HCL (Table 3). Because there were no differences in crop yields in CSL and HCL, significant correlations were not expected. In RSL, changes in SOC explained 38% of the variability in grain yield while those of available P explained 44%. At the same site, MWD was also highly correlated with SOC and total N concentrations and moderately with K^+, Ca^{+2}, Mg^{+2}, and CEC (Table 3). Variations in SOC concentration explained 66% of the variability in MWD while those in total N explained 88%. In CSL, MWD was moderately correlated with SOC and total N concentrations. In HCL, MWD was not correlated with any parameter of soil fertility. Two pedotransfer functions for predicting grain yield in the sloping silt loam and stover yield in the nearly flat silt loam were identified:

$$\text{Grain}=-2.874+0.082\ \text{Available P}+0.024\ K^+ \quad R^2=0.77,\quad P<0.01 \qquad [1]$$

$$\text{Stover}=3.943-21.414\ \text{Total N}+0.281\ \text{SOC} \quad R^2=0.45,\quad P<0.01 \qquad [2]$$

DISCUSSION

The data presented in this study after 4 yr of stover management show that removal of 25 to 50% of the stover from NT continuous corn systems reduced nutrient pools and soil structural stability. The total SOC pool decreased with stover removal rates as low as 25%, in accord with the results of a previous study after 2½ yr of stover management (Blanco-Canqui and Lal, 2007). The decrease in the remaining soil fertility indicators generally occurred with high rates of stover removal.

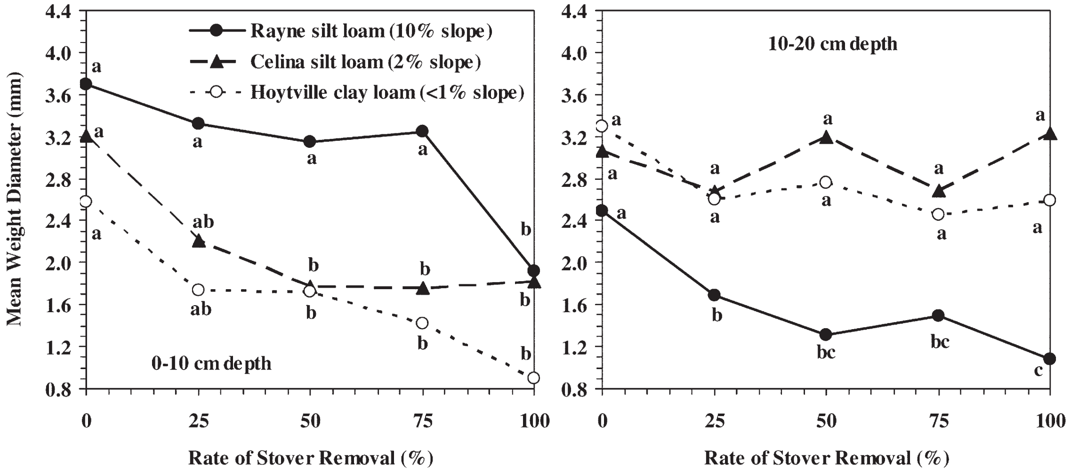

Fig. 4. Mean weight diameter of aggregates for each of the five stover treatments for the 0- to 10- and 10- to 20-cm soil depths for three soils. Mean values followed by the same letter are not significantly different.

The consistent decrease of K^+ with ≥75% of stover removal across the three soils also reflects the high content of K in crop residues. The site specificity of high stover removal impacts is illustrated by the larger reductions in the total SOC pool (14.9 Mg ha^{-1}), the total N pool (1.1 Mg ha^{-1}), the available P concentration (20 mg kg^{-1}), and the C/N ratio in the sloping silt loam than in the relatively flat silt loam (8.8 Mg ha^{-1} of SOC and 0.80 Mg ha^{-1} total N) and clay loam (6.5 Mg ha^{-1} SOC) in the 0- to 20-cm depth (Fig. 1). These results suggest that soil textural and topographic differences among sites influenced the stover removal impact. High stover removal from the sloping silt loam not only reduced the concentration of all macronutrients but the effects were measurable in both soil depths, unlike in the other two soils where reductions were primarily confined to the 0- to 10-cm depth. It is hypothesized, however, that impacts on nutrient pools in the nearly level silt loam and clay loam will manifest more in the long term (>5 yr) under continued removal of stover.

The large decreases in N pools with high stover removal supports the conclusions of Karlen et al. (1994) in which complete removal (100%) reduced total N by 30% in silt loam soils. Data also agree with those reported in semihumid tropical silty clay and clayey soils in central Mexico, where removal of stover at rates of 33% significantly reduced the total N and extractable P (Salinas-Garcia et al., 2001). The small or no impact of stover removal on available P in the nearly level silt loam and clay loam supports the conclusions in a silty clay loam by Larson et al. (1972), who concluded that, unlike in tropical environments, in temperate zones soil available P is less readily changed than C and N concentrations under stover removal. The reduction in available P, K^+, Ca^{+2}, Mg^{+2}, and CEC with stover removal contrasts, however, with the lack of stover removal effects observed by Karlen et al. (1984, 1994) after 4 and 10 yr of stover management, respectively. The few comprehensive studies reporting the impacts of partial stover removal on nutrient pools for the U.S. Corn Belt region limits further comparison of our results.

Table 2. Corn grain and stover yield under stover management across three soils in Ohio for the 2004 through 2007.

Soil	Stover removal rate	Grain yield				Stover yield			
		2004	2005	2006	2007	2004	2005	2006	2007
	%	Mg ha^{-1}							
Rayne silt loam	100	7.5	6.3	7.3	7.5	7.2	6.2	5.1	5.3
	75	7.8	6.7	8.4	8.7	7.6	6.6	5.7	6.1
	50	9.0	8.8	8.7	8.9	8.6	8.6	5.7	6.5
	25	8.5	10.2	10.4	10.4	8.1	10.1	6.4	6.6
	0	9.3	10.3	10.6	10.1	9.2	10.2	6.7	6.8
	LSD (0.05)	1.8	1.2	1.3	1.0	2.0	2.1	1.5	1.3
Celina silt loam	100	7.1	6.0	11.5	10.8	6.6	6.1	7.5	7.8
	75	7.9	6.1	11.7	10.3	7.3	6.1	7.6	7.5
	50	7.6	6.1	11.8	10.1	7.0	6.2	8.2	7.6
	25	8.0	5.9	11.9	10.6	7.7	6.1	6.7	7.7
	0	7.7	6.1	11.5	10.7	7.2	6.3	8.4	7.9
	LSD (0.05)	1.3	0.3	0.6	0.8	0.8	0.3	0.8	0.2
Hoytville clay loam	100	8.1	7.1	9.6	9.1	7.9	7.0	7.1	6.9
	75	8.2	7.1	10.0	9.3	8.0	7.1	7.9	6.6
	50	8.0	7.6	10.2	9.4	7.8	7.4	7.5	7.1
	25	8.2	7.8	10.3	9.1	7.8	7.7	7.3	6.8
	0	8.3	7.6	10.1	9.2	8.1	7.5	7.7	6.9
	LSD (0.05)	0.4	0.7	0.6	0.4	0.3	0.6	0.7	0.4

The reduction in nutrient pools partly explained the reduction in grain yield in the sloping silt loam (Table 3). Available P and K^+ were significant predictors (Eq. [1]) of grain yield while total SOC and N concentrations were predictors of stover yield (Eq. [2]) at this site. Despite the annual application of N on all plots at a rate of 150 kg ha^{-1}, grain and stover yields from the plots without stover were lower than those from plots with stover in the sloping silt loam, which indicates that normal fertilization was insufficient to offset the adverse effects of complete stover removal on soil fertility and other plant-growth factors such as soil temperature, plant-available water, and compaction, which was also reported by Blanco-Canqui and Lal (2007). The smaller changes in available P, Ca^{+2}, and Mg^{+2} in the nearly level soils may explain the lack of stover removal influences on crop yields.

The increase in soil pH with stover removal in the clayey soil agrees with Morachan et al. (1972), who reported that soil pH decreased in a silty clay loam from 5.3 to 5.1 and 4.8 with the application of 4 and 16 Mg ha^{-1} of stover, respectively, whereas it contrasts with the results of Karlen et al. (1994), which showed no impacts of stover removal on soil pH in NT silt loams. The decrease in pH in heavily mulched soils may be attributed to the decomposition of stover near the surface layers (Karlen et al., 1984). The increase in EC with stover removal is also in accord with the conclusions of Shaw and Mask (2003), who reported that residue removal from a NT corn–soybean–wheat (*Triticum aestivum* L.) rotation increased EC by 5% in a loam soil.

Table 3. Correlation coefficients among selected soil properties and crop yield. Only study sites with significant correlations among the measured parameters are reported.

Soil property	Grain yield	Mean weight diameter of aggregates	
		Rayne silt loam	Celina silt loam
Organic C, g kg^{-1}	0.62**	0.80***	0.50*
Total N, g kg^{-1}	0.47†	0.86***	0.34 NS‡
Organic C, Mg ha^{-1}	0.61*	0.82***	0.65**
Total N, Mg ha^{-1}	0.47†	0.94***	0.51*
C/N ratio	0.50*	0.07 ns	0.41 NS
Available P, mg kg^{-1}	0.66***	0.11 ns	0.07 NS
Exchangeable K^{+}, mg kg^{-1}	0.56*	0.51*	0.41 NS
Exchangeable Ca^{+2}, mg kg^{-1}	0.54*	0.58*	−0.03 NS
Exchangeable Mg^{+2}, mg kg^{-1}	0.50*	0.59*	0.01 NS
pH	0.05 NS	−0.19 NS	−0.32 NS
Electrical conductivity, dS m^{-1}	−0.21 NS	0.12 NS	−0.03 NS
Cation exchange capacity, cmol$_c$ kg^{-1}	0.55*	0.59*	0.30 NS

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Significant at the 0.10 probability level.

‡ NS = not significant.

The decrease in aggregate stability with stover removal agrees with the results reported by Blanco-Canqui et al. (2006) for the same stover experiments after 1 yr. Our results disagree, however, with those of Karlen et al. (1994), who found no impacts of complete stover removal on aggregate stability after 10 yr of stover management. These contrasting trends suggest that differences in soil, topography, the amount of stover produced, management, and climate influence stover removal impacts. The increase in the MWD of aggregates with increasing SOC pool (Table 3) suggests that stover removal reduced macroaggregates and increased microaggregates by reducing the stover-derived organic binding agents required for the hierarchal formation of aggregates. The decrease in SOC concentration can be used as a sensitive indicator of soil structural decline with stover removal.

The high correlation between aggregate stability and total N, K^{+}, Ca^{+2}, Mg^{+2}, and CEC (Table 3), especially in the sloping silt loam, indicates that aggregation is also a sensitive indicator of changes in the nutrient pool because aggregate stability dynamically integrates soil physical, chemical, and biological processes (e.g., SOM decomposition, nutrient cycling, and microbial processes) (Karlen et al., 1994). It also confirms that soils with stable macroaggregates often store more SOC, N, and available P than those dominated by microaggregates in that stable aggregates reduce the rapid mineralization of SOM (Elliott, 1986). The positive MWD and CEC correlation in the sloping silt loam suggests that the return of corn stover increases the concentration of labile SOM, which increases both aggregate stability and CEC.

The rapid nutrient depletion, particularly in the sloping soil, suggests that stover removal can lead to nutrient deficiencies in the long term, requiring additional N, P, and K fertilizers to compensate for the losses. This concern must be considered before undertaking a large-scale removal of stover. Data also suggest the need for a comprehensive nutrient budget analysis under stover removal by quantifying inputs (e.g., fertilization and stover return) and outputs (e.g., stover removal, loss of nutrients through runoff and leaching, and emissions of CO$_2$, CH$_4$, and NO$_2$). Stover removal has direct and indirect effects on soil fertility. First, it causes a direct loss of nutrients by removing nutrient-rich stover. Second, it increases the risks for nutrient losses through erosion (Blanco-Canqui and Lal, 2007). Third, it changes the microclimate (e.g., soil temperature, water content, and evaporation) and modifies the soil physical (e.g., aggregate detachment and exposure of aggregate-protected C), chemical (e.g., redox and solution), and biological (e.g., acceleration of SOM mineralization and reduction in microbial activity) processes, which results in reduced nutrient pools.

CONCLUSIONS

This study shows that stover removal for biofuel production and other industrial uses decreases soil fertility and structural stability. Complete (100%) stover removal reduces the total N pool, the available P, K^{+}, Ca^{+2}, and Mg^{+2}, and the CEC while removal at rates ≥50% decreases aggregate stability. Data also show that the impacts of stover removal are greater in sloping soils than in flat and glaciated soils, suggesting that short-term removal impacts are soil specific, which underscores the need for further assessment of stover removal impacts by soil and ecoregion. Based on the data from this and the previous studies, it is concluded that only about 25% of stover might be available for removal. This threshold level is principally based on the need to maintain SOC levels and structural stability, which were reduced with removal at rates as low as 25 and 50%, respectively. It is also recommended that further long-term monitoring of changes in soil fertility indicators is warranted to strengthen the short-term (4-yr) database and to conclusively establish the threshold levels of stover removal for these soils. Overall, our results indicate that proposals for stover harvesting as biofuel must carefully and objectively consider the negative effects that a high (>25%) removal of stover has on soil fertility and structural stability.

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