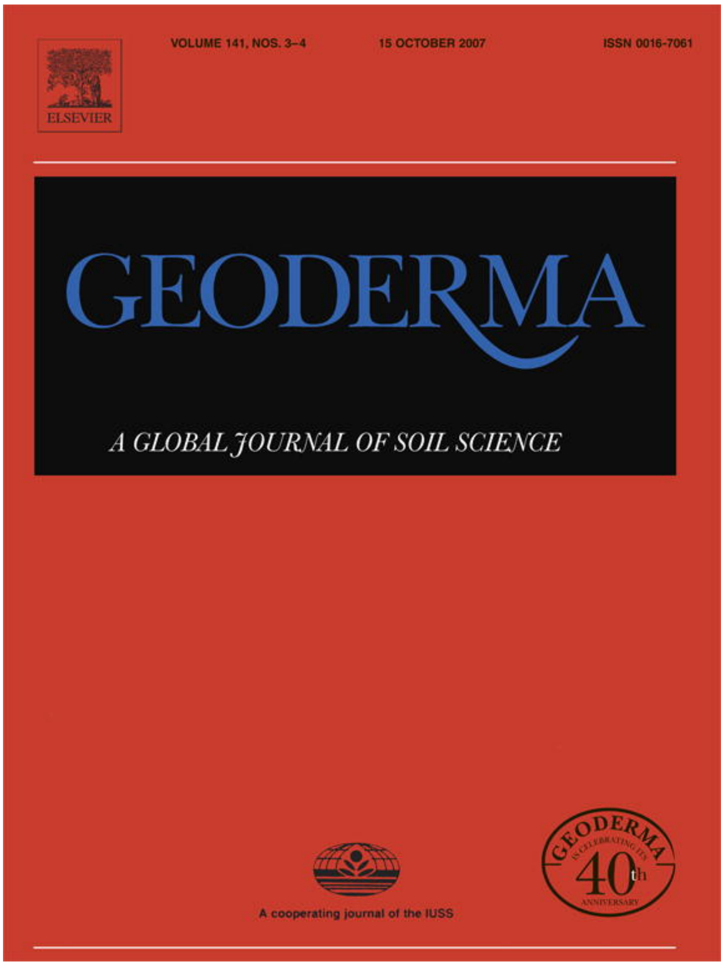
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Soil and crop response to harvesting corn residues for biofuel production

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Abstract

Corn (*Zea mays* L.) stover is considered one of the prime lignocellulosic feedstocks for biofuel production. While producing renewable energy from biomass is necessary, impacts of harvesting corn stover on soil organic carbon (SOC) sequestration, agricultural productivity, and environmental quality must be also carefully and objectively assessed. We conducted a 2 1/2 year study of stover management in long-term (>8 yr) no-tillage (NT) continuous corn systems under three contrasting soils in Ohio to determine changes in SOC sequestration, CO_2 emissions, soil physical properties, and agronomic productivity. These measurements were made on a Rayne silt loam (RSL) (fine-loamy, mixed, active, mesic Typic Hapludult) with 6% slope, Celina silt loam (CSL) (fine, mixed, active, mesic Aquic Hapludalfs) with 2% slope, and Hoytville clay loam (HCL) (fine, illitic, mesic Mollic Epiaqualfs) with <1% slope. Stover treatments consisted of removing 0, 25, 50, 75, and 100% of corn stover following each harvest. At the start of the experiment in May 2004, these percentages of removal corresponded to 5, 3.75, 2.5, 1.25, and 0 Mg ha^{-1} yr^{-1} of stover left on the soil surface, respectively. Annual stover removal rate of >25% reduced SOC and soil productivity, but the magnitude of impacts depended on soil type and topographic conditions. Stover removal rate of 50% reduced grain yield by about 1.94 Mg ha^{-1}, stover yield by 0.97 Mg ha^{-1}, and SOC by 1.63 Mg ha^{-1} in an unglaciated, sloping, and erosion-prone soil ($P<0.05$). The initial water infiltration rates were significantly reduced by >25% of stover removal on a RSL and CSL. Plant available water reserves and earthworm population were significantly reduced by 50% of stover removal at all soils. Increases in soil compaction due to stover removal were moderate. Stover removal impacts on SOC, crop yield, and water infiltration for HCL were not significant. Results from this study following 2 1/2 yr of stover management suggest that only a small fraction (≤25%) of the total corn stover produced can be removed for biofuel feedstocks from sloping and erosion-prone soils.

Keywords: Corn stover; Soil organic carbon; Biofuel production; Crop yield; Soil compaction

1. Introduction

Producing energy from renewable resources to reduce both over-reliance on imported fossil fuels and intensity of greenhouse gas emissions is a high priority (Herrera, 2006; Graham et al., 2007). One of the potential renewable energy feedstocks is corn stover because of its high cellulose content and abundance (Pacala and Socolow, 2004). Stover is the nongrain part of a corn plant which is left on the soil surface after harvest such as stalk, husk, leaves, and cobs (Wilhelm et al., 2004). It represents the largest amount of crop biomass produced in the U.S., mostly in the Corn Belt region, estimated at 238 million tons yr^{-1} (Tg yr^{-1}) (Sokhansanj et al., 2002). National interest for a large-scale harvesting of corn stover as biofuel feedstocks is high, technologies for stover conversion to liquid biofuel are well advanced, and the ethanol plant construction industry is booming (Somerville, 2006).

While increasing biofuel production is important to reducing dependence on foreign oil, removal of corn stover for biofuel production may be “robbing Peter to pay Paul” (Lal and Pimentel, 2007). Corn stover retention is indispensable to achieving effective soil and water conservation (Lal, 2005). An excessive removal of corn stover for biofuel production may adversely affect SOC, nutrient cycling, soil tilth, soil water reserves, biotic activity, and crop yields (Wilhelm et al., 2004; Lal et al., 2004). It may reduce soil water storage, alter soil temperatures regimes, reduce soil structural stability, increase

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soil compaction, decrease water infiltration, and increase soil erosion and non-point source pollution.

While little, if any, crop residues should be removed from soils on sloping lands and from those prone to wind erosion, it is hypothesized that some amount of crop residues may be removed from those with poor internal drainage, fine texture and in regions with wet springs and sub-optimal soil temperature regime. Thus, an important but unresolved question is how much stover can be removed without jeopardizing SOC sequestration, soil and environmental quality, and agronomic sustainability? Removal of excess corn stover may even be beneficial in some soils in terms of farm economy and crop yields because excessive stover mulch causes planting difficulties and, in cool and temperate regions, slows soil warming in spring and reduces plant emergence resulting in lower crop yields (Wolfe and Eckert, 1999; Mann et al., 2002).

While the negative impacts of complete stover removal are foreseeable (Karlen et al., 1994), the impact of partial stover removal on SOC, soil physical quality, and crop productivity has not been fully resolved. Yet, it is precisely this information that is needed for determining the maximum permissible rates of stover removal and developing decision support systems for a judicious management of crop residue for essential but competing uses. Some reports indicate that 30% to 50% of the total corn stover production in the U.S. Corn Belt region may be removed for biofuel production (Kim and Dale, 2005; Graham et al., 2007). These estimates are, however, based on the residue requirements for reducing soil erosion risks and do not consider the additional requirements for sequestering SOC, off-setting CO_2 emissions, maintaining soil fertility, recycling nutrients, sustaining crop yields, and maintaining the overall soil quality (Lal, 2005). Studies specifically designed to assess the effects of corn stover removal from NT continuous corn, a prime candidate for stover harvesting, are needed to determine the threshold levels of stover removal. Thus, the objectives of this study were to comprehensively assess the impacts of harvesting corn stover on SOC sequestration, CO_2 emissions, soil physical quality, and agronomic productivity across three soils under long-term NT systems in Ohio after 2 1/2 yr of stover management.

2. Materials and methods

2.1. Description of the study sites

Three sites with contrasting soil textural and topographic characteristics under long-term (>8 yr) NT management in Ohio were selected in 2004. Two sites under glaciated soils (Celina silt loam and Hoytville clay loam) and one under an unglaciated soil (Rayne silt loam) were selected for the study. Detailed information on the study sites including soil characteristics and management history is presented in Table 1. At each site, a randomized complete block design with five corn stover treatments and three replications was established in 3×3 m plots in May 2004 before corn planting. Stover treatments consisted of removing 0, 25, 50, 75, and 100% of corn stover from the previous crop season. At the start of the experiment in May 2004, these percentages of removal corresponded to 5, 3.75, 2.5, 1.25, and 0 Mg ha^{-1} yr^{-1} of stover left on the soil surface at each site, respectively. All sites were managed under NT continuous corn, and the stover produced at harvest was distributed in the corresponding treatments in 2004 and 2005.

While the same percent of stover was removed from each plot throughout the study period, the actual amount of stover distributed in each plot after each harvest differed from the amount of stover at the experiment onset as the weight of stover produced at harvest varied from year to year at each site (Table 2). For this study, corn stover and ears were manually harvested from the center two rows of each plot in October 2006, and results of stover and grain yields were reported at water content of 155 g kg^{-1}.

2.2. Measurement of CO_2 fluxes and soil carbon

Gas samples for the CO_2 analyses were collected from each treatment and site monthly during the crop growing season between May and September 2006 using the closed soil chamber method (Jacinthe and Dick, 1997). Chambers constructed from a PVC pipe with a diameter of 15 cm and length of 30 cm and equipped with water through, PVC endcap,

Table 1
Information on location and soil and management characteristics of the three study sites in Ohio

Location	Coordinates	Soil series	Taxonomic classification	Soil description	Slope (%)	Management before experiment initiation
North Appalachian Experimental Watersheds, Coshocton	40°16′19″N and 81°51′35″W	Rayne silt loam (638 g kg^{-1} silt and 153 g kg^{-1} clay)	Fine loamy, mixed, mesic Typic Hapludults	Sloping and water erosion-prone soils. Unglaciated, deep, and well drained soils on weathered shale and fine-grained sandstone	6	35-yr NT continuous corn, 150 kg N ha^{-1} applied as NH_4NO_3, and herbicides applied for controlling weeds.
Western Agricultural Experiment Station, South Charleston	39°49′31″N and 83°38′04″W	Celina silt loam (558 g kg^{-1} silt and 216 g kg^{-1} clay)	Fine, mixed, active, mesic Aquic Hapludalfs	Glaciated and relatively nearly soils, very deep, moderately well drained on high-lime loamy till plains and moraines	2	15-yr NT continuous corn/soybean rotation
Northwestern Agricultural Experiment Station, Hoytville	41°11′24″N and 83°47′05″W	Hoytville clay loam (341 g kg^{-1} silt and 437 g kg^{-1} clay)	Fine, illitic, mesic Mollic Epiaqualfs	Glaciated and nearly level clayey soils on till-floored lake plains. Very cohesive, very deep, and very poorly drained soils under occasional anaerobiocity	<1	8-yr continuous corn/soybean rotation under NT with alternate year disking

Table 2
Amount of stover (Mg ha^{-1}) produced at harvest at each soil in 2004 (6 months after experiment initiation) and 2005 (17 months after experiment initiation)

Stover removal (%)	Harvesting periods					
	2004			2005		
	Rayne	Celina	Hoytville	Rayne	Celina	Hoytville
	Silt loam	Silt loam	Clay loam	Silt loam	Silt loam	Clay loam
0	9.15	7.21	8.05	10.15	6.25	7.45
25	8.11	7.66	7.80	10.11	6.10	7.70
50	8.61	7.02	7.75	8.61	6.20	7.40
75	7.62	7.27	8.03	6.62	6.14	7.10
100	7.21	6.59	7.91	6.21	6.10	6.95
LSD[a]	2.4	1.51	0.52	3.20	0.40	0.91

[a] Least significant differences.

and sampling port were used for the gas sampling. Details of construction, components, and protocols for use of the chambers are discussed by Jacinthe and Dick (1997). The chambers, one per plot, were driven into a moist soil to a depth of 10 cm and remained in place throughout the study period.

Chambers were left open at all times except during sampling when they were tightly closed with the PVC endcap on top and sealed with water contained in the chamber coupling. Gas samples (about 25 ml) were collected at 0, 30, and 60 min. some time between 11:00 and 15:00 h and stored in pre-evacuated and rubber-sealed vials. The CO_2 concentrations in the vials were measured using a Shimadzu GC-14A gas chromatograph (Alltech, Deerfield, IL). Intact soil cores of 5.4 cm in diameter were collected from 0- to 2-, 2- to 4-, 4- to 6-, 6- to 10-, 10- to 15-, 15- to 20-, and 20- to 30-cm soil depth intervals for the determination of total SOC on a volume basis in October 2006. Samples were air-dried, ground, and passed through a 250 μm sieve to determine SOC concentration by the dry combustion method (900 °C) using a CN analyzer (Vario Max, Elementar Americas, Inc., Hanau, Germany) (Nelson and Sommers, 1996). The baseline data for total SOC collected just prior to experiment onset was 30±3 g kg^{-1} (mean±SD) for RSL, 26±3 g kg^{-1} for CSL, and 28±2 g kg^{-1} for HCL. Differences in SOC among experimental units within each site at the start of the experiment were not significant ($P>0.10$).

2.3. Measurement of soil physical properties

Soil temperature was monitored monthly during the growing season in 2006 at the 5-cm soil depth at 2 PM using dual thermocouple thermometer probes (Cole-Parmer Instruments, Co., Vernon Hills, IL; McInnes, 2002). Bulk density determined by the core method was measured monthly on intact small 5.4 cm diameter by 6 cm high soil cores extracted from 0- to 6-cm depth (Grossman and Reinsch, 2002). Cone index was measured monthly for the 0- to 5-cm depth by a static hand cone penetrometer (Eijkelkamp, Giesbeek, The Netherlands) (Lowery and Morrison, 2002). Measured cone index values were adjusted to a common value of gravimetric water content to avoid bias due to differences in soil water content. Adjustment procedures were those used by Busscher and Bauer (2003) and (Blanco-Canqui et al., 2006). Prior to harvest, in October 2006, 5.4- by 6-cm intact soil cores were collected from each plot for all sites to determine soil water retention at −30 kPa by the tension table and −1500 kPa by pressure plate extraction to compute plant available water (PAW) (Dane and Hopmans, 2002). A double-ring infiltrometer was used to determine the water infiltration rates in each plot for 3 h in October 2006 (Reynolds et al., 2002). Earthworm numbers present in 0.0094 m^3 volume (0.0625 m^2 surface area × 0.15 m depth) of soil were manually counted in each plot at the time of infiltration measurements (Edwards and Bohlen, 1996).

2.4. Statistical analyses

A one-way ANOVA model was used to determine whether differences in SOC, CO_2 emission, soil water retention and transport parameters, soil compaction, earthworm population, and crop yield among the five stover treatments were significant. Correlation analyses between SOC concentration and PAW and soil compaction parameters, and multiple regression analyses to determine pedotransfer functions for predicting grain and stover yields were performed. All statistical analyses were conducted using SAS (SAS Institute, 2007). The statistical differences are reported at the 0.05 probability level unless otherwise stated.

3. Results and discussion

3.1. Soil organic carbon and CO_2 emission

Stover removal had a significant adverse impact on SOC concentration ($r>0.95$; $P<0.001$), which decreased with increase in rate of stover removal in the silt loam soils (RSL and CSL) but not in the clayey soil (HCL) over the study period of 2 1/2 yr (Fig. 1). On the HCL, although the SOC concentration decreased linearly with increase in stover removal rate, differences among the five stover treatments were not significant. On the RSL, removal of 25% of stover did not

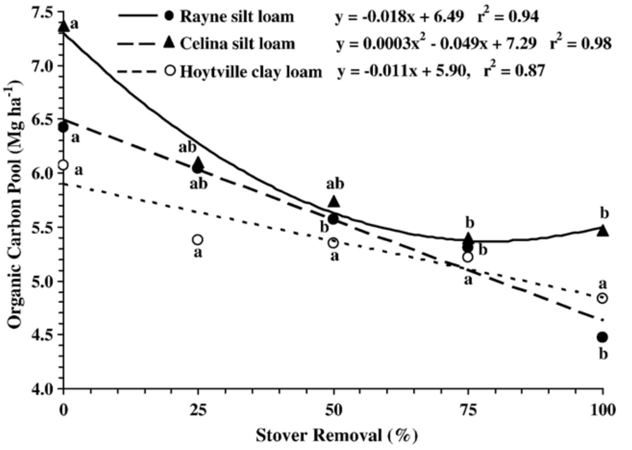

Fig. 1. Effect of annual stover removal on soil organic carbon in the 0- to 2-cm soil depth for a glaciated soil (Rayne silt loam) and unglaciated soils (Celina silt loam and Hoytville clay loam) after 2 1/2 yr of stover management. Means with the same letter are not significantly different within the same soil.

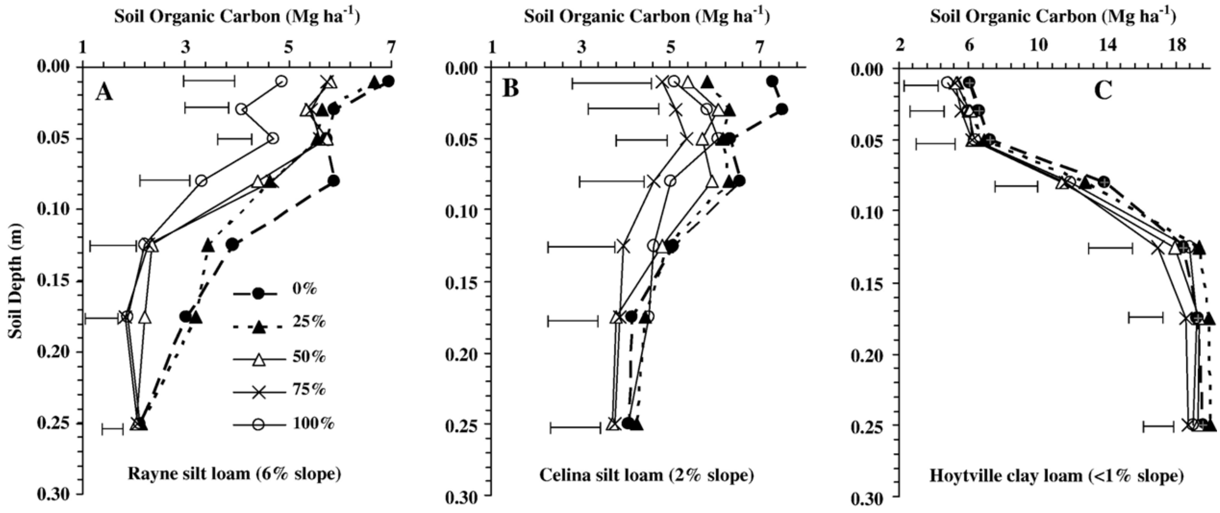

Fig. 2. Depth distribution of soil organic carbon content on a volume basis as affected by five different rates of stover removal (0, 25, 50, 75, and 100%) under three contrasting (A, B, C) NT soils in eastern U.S. Corn Belt region. Error bars signify least significant differences values at each soil depth interval.

significantly reduce SOC concentration; however, removal rates >25% dramatically reduced SOC. Complete removal of stover reduced SOC by 1.95 Mg ha^{-1} in the 0- to 2-cm depth for RSL.

Total SOC in the upper 30 cm layer in the RSL was 32.4± 1.6 Mg ha^{-1} under <25% of stover removal, 27.7±0.5 Mg ha^{-1} under plots with stover removal between 25% and 75%, and 23.2±1.8 Mg ha^{-1} in plots with complete stover removal after 2 1/2 yr of stover management (Fig. 2). On the CSL, removal of stover up to 50% did not reduce SOC, but removal at higher percentages significantly reduced SOC by 1.9 Mg ha^{-1} in the 0- to 2-cm soil depth. The SOC decreased quadratically with increase in stover removal for CSL, indicating that decreases in SOC reached a plateau with stover removal above 75%. Total SOC in the 0- to 30-cm depth in the CSL was 40.9±1.3 Mg ha^{-1} in plots with all stover returned, 38.2±1.0 Mg ha^{-1} with 25% Mg ha^{-1} of stover removed, and 35.2±2.1 Mg ha^{-1} with complete removal.

These results show that the magnitude of depletion of SOC by stover removal was directly proportional to the reduction in the amount of stover-based C input in these silt loam soils. The negative impacts of stover removal on SOC may depend on soil characteristics such as clay content, drainage characteristics, and slope gradient (Wilhelm et al., 2004). Depletion of SOC by stover removal was more drastic in silt loam than in clayey soils over the short 2 1/2 year period.

Little or no reduction in SOC in clayey soils may be explained by their restricted drainage and occasional anaerobiocity, and high cohesiveness that reduces or even inhibits the

Table 3
Stover removal impacts on CO_2 fluxes and soil temperature

Soil and Slope	Stover Removal (%)	CO_2 fluxes (g CO_2–C m^{-2} day^{-1})					Temperature (°C)				
		May	June	Jul	Aug	Sept	May	June	Jul	Aug	Sept
Rayne silt loam	0	2.8	1.8	1.8	0.4	1.1	21.2	23.9	25.2	25.5	22.1
	25	3.3	1.7	1.8	1.0	1.5	23.9	24.8	27.7	28.4	23.2
	50	3.0	1.9	1.7	2.0	1.4	25.0	26.0	30.9	31.1	23.8
	75	3.3	1.5	1.5	1.7	1.6	26.4	27.6	34.0	34.1	24.8
	100	4.3	2.3	2.3	2.6	2.1	28.0	28.7	35.6	35.2	26.2
	LSD[a]	1.9	0.8	1.1	3.0	1.9	2.0	1.9	2.1	1.8	1.5
Celina silt loam	0	3.6	1.5	1.0	2.5	1.3	22.0	23.5	23.3	27.0	22.6
	25	3.1	1.6	1.5	2.0	1.0	22.7	24.1	23.9	28.3	23.5
	50	4.3	1.0	1.4	1.9	2.7	23.2	24.2	26.7	30.3	23.9
	75	4.0	1.4	1.4	1.7	2.3	25.1	26.1	27.6	30.7	25.3
	100	3.2	0.8	1.1	1.4	2.2	25.6	27.0	28.0	31.7	26.1
	LSD[a]	4.8	0.7	1.9	3.4	3.1	1.1	2.1	1.3.	1.9	1.8
Hoytville clay loam	0	0.6	0.5	0.5	1.1	1.7	22.8	23.6	27.3	27.3	25.0
	25	1.1	0.8	0.8	0.8	1.1	24.0	24.8	28.3	29.7	26.2
	50	1.0	1.0	1.0	1.1	1.6	26.6	27.5	31.1	32.3	27.3
	75	1.6	0.7	1.3	0.6	1.4	29.8	30.7	32.3	33.3	29.2
	100	0.7	0.6	1.5	1.8	1.0	30.6	31.6	33.5	34.3	29.3
	LSD[a]	2.6	0.8	1.4	3.2	1.1	1.4	1.6	2.0	1.9	1.7

[a] Least significant differences.

decomposition of organic matter, unlike in silt loam soils with higher rates of water and air fluxes which enhance decomposition (Needelman et al., 1999). Saturation of SOC in clayey soils may be another reason for little change during the 2 1/2 year period. Changes in SOC by stover removal in soils where C concentration is at or close to steady state equilibrium may take a longer time than the observation period of this study. When the soil is at saturation level with SOC, it can not absorb more C as SOC is in equilibrium with the atmosphere (Six et al., 2002). At this point, the soil returns as much C as it absorbs. Site-specific factors affecting the time that it takes for a soil to reach a maximum saturation level includes initial SOC concentration, soil type, clay content, tillage and cropping system, and climate conditions (Hooker et al., 2005). Understanding the saturation level of SOC for each soil is necessary to ascertain the potential impacts of stover removal on SOC. In contrast to the data on SOC, stover removal did not significantly affect CO_2 emissions for any of the three soils ($P > 0.10$; Table 3). Although mean daily CO_2 flux for normal stover treatments (100% mulch) tended to be higher than those for treatments without stover in RSL and HCL, differences were not significant due to the high variability in daily CO_2 fluxes. The coefficient of variation in CO_2 flux was 44% for RSL, 56% for HCL, and 50% for CSL. High variation in CO_2 flux from soils covered by crop residue mulch is commonly observed (Jacinthe et al., 2002). In contrast to some reports of significant losses in soil C through CO_2 emissions from mulched NT soils (Jacinthe et al., 2002), this study showed that mulched soils did not exhibit higher C by emissions compared to the unmulched control. No significant increase in rate of CO_2 emission from soils with high rates of stover mulch implies that gains in SOC sequestration are greater than losses as CO_2. More intensive measurement of CO_2 emissions is warranted to quantify losses of SOC in greater detail.

3.2. Water infiltration rates and earthworm population

The rate of stover removal had a strong adverse effect on water infiltration rate for RSL (Fig. 3A), a small effect on CSL (Fig. 3B), and no effect on HCL (Fig. 3C). Stover removal above 50% reduced initial water infiltration rates (up to about 1 h) by a factor of 4 in RSL and 2 in CSL. Effects of stover removal on the final infiltration rate were small, but a difference was mostly significant between complete stover removal (0 mulch) and normal stover rate. The reduction in water infiltration rate with stover removal for RSL and CSL was probably due to soil surface sealing or crusting, and consolidation caused by raindrops impacting the bare soil surface. Furthermore, unmulched soils had lower surface-connected earthworm burrows than mulched soils. Surface sealing and crusting by impacting raindrops probably clogged the initially open-ended burrows and other biopores on unmulched soils, thereby reducing water infiltration. Studies have shown that earthworm burrows are rapid conduits and preferential pathways of water and air flow and their perturbation unfavorably impacts infiltration (Shipitalo and Butt, 1999).

Stover removal at rates above 25% drastically reduced the number of earthworms in all soils. In RSL, the number of earthworms (160 ± 51 per m^2) in plots with ≤25% of stover removed was about 3.4 times higher than in plots with >25% of stover removed (47 ± 36 per m^2). In CSL, the number of earthworms (96 ± 25 per m^2) was 2.6 times higher in plots with <25% of stover removed than in plots with >25% of stover removed (18 ± 17 per m^2). The large reduction of earthworm population by stover removal rates of >25% in silt loam soils with a short period of 2 1/2 years was accompanied by an undesirable impact on water infiltration. In poorly drained and occasionally anaerobic clayey soils (HCL), earthworms were completely eliminated (0 ± 0 per m^2) by removing 50% of stover, and plots receiving <50% of stover removed had earthworm populations of 40 ± 22 per m^2. The elimination of

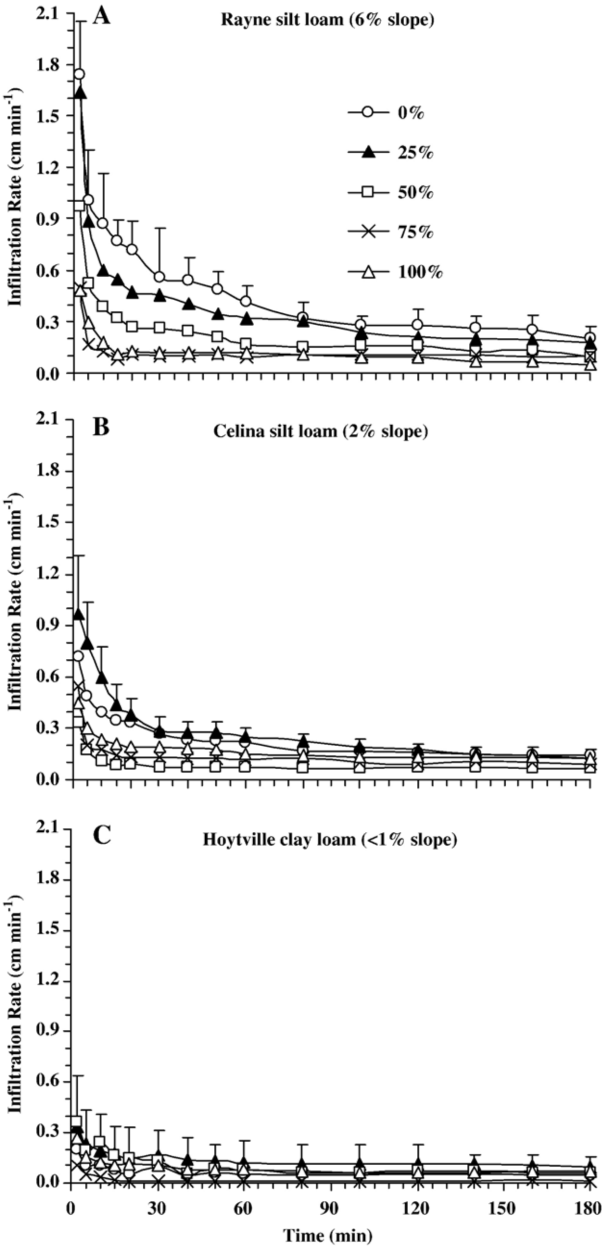

Fig. 3. Rates of water infiltration for the three (A, B, C) NT soils managed under five rates of stover removal (0, 25, 50, 75, and 100%). Error bars signify least significant differences values at each measurement time interval.

earthworms by stover removal in clayey soils did not, however, affect water infiltration rate because of low antecedent infiltration. Besides, there were fewer earthworms in clayey than in silt loam soils. Stover removal adversely impacted water infiltration rate in silt loam soils particularly in sloping and erosion-prone environments (Shipitalo and Butt, 1999). The reduction in water infiltration rate may result in increased runoff and soil erosion rates and thus increased risks of non-point source pollution. The large decrease in earthworm population by stover removal may not only reduce water infiltration rate but also impair critical physical (such as macropore development, aggregate formation and stability, aeration), chemical (such as pH, organic matter decomposition, nutrient cycling), and biological (such as microbial activity) soil processes (Karlen et al., 1994).

3.3. Plant available water reserves and soil compaction

Stover removal had a large negative impact on PAW reserves in all soils measured within the 0- to 6-cm depth. The PAW decreased linearly with increase in the rate of stover removal for silt loam and quadratically for clayey soils ($P<0.01$; Fig. 4A). Stover removal at $\geq 50\%$ significantly reduced PAW on both silt loam soils. For the 6-cm soil depth, removal of 75% of stover reduced PAW by 0.5 on the RSL and by 0.26 cm on the CSL. On the HCL, removal of stover at a rate of 50% reduced PAW by 0.66 cm (Fig. 4A). Our results suggest that stover removal decreased PAW by reducing SOC concentration. Indeed, the PAW values were strongly and positively correlated with changes in SOC concentration in RSL ($r=0.60$; $P<0.02$) and HCL ($r=0.73$; $P<0.01$). The stover-derived organic materials increase PAW by increasing the specific surface area of soil particles and promoting aggregation, which increase the soil water retention capacity (Kladivko, 1994).

Stover removal caused moderate increase in soil compaction as measured by bulk density (Fig. 4B) and cone index (Fig. 4C) in the surface 0- to 10-cm depth. Increase in soil compaction due to stover removal was more pronounced in silt loam than in clayey soils. On the RSL, removal of stover at as low as 25% rate increased bulk density by 0.10 Mg m^{-3}, and removal at $>50\%$ increased cone index by 0.17 MPa. On the CSL, removal of stover at $>50\%$ rate increased bulk density by 0.15 Mg m^{-3} and cone index by 0.24 MPa. The moderate increase in soil compaction over a period of 2 1/2 years are in accord with the results reported with one year of stover removal (Blanco-Canqui et al., 2006). Greater SOC at higher mulch rates reduced soil strength properties of silt loam soils. Indeed, both cone index ($r\approx 0.62$; $P<0.02$) and bulk density ($r\approx 0.50$; $P<0.05$) increased linearly with a decrease in SOC concentration in treatments with high rate of stover removal. Removal of stover at rates >25% increased soil compaction although the magnitude of increase was moderate. Stover retention protects the soil against the combined detrimental effects of raindrop impact, surface sealing, crusting, abrupt fluctuations of wetting and drying cycles of the soil, and animal and wheel traffic, which cause consolidation and densification of the surface layers (Wilhelm et al., 2004).

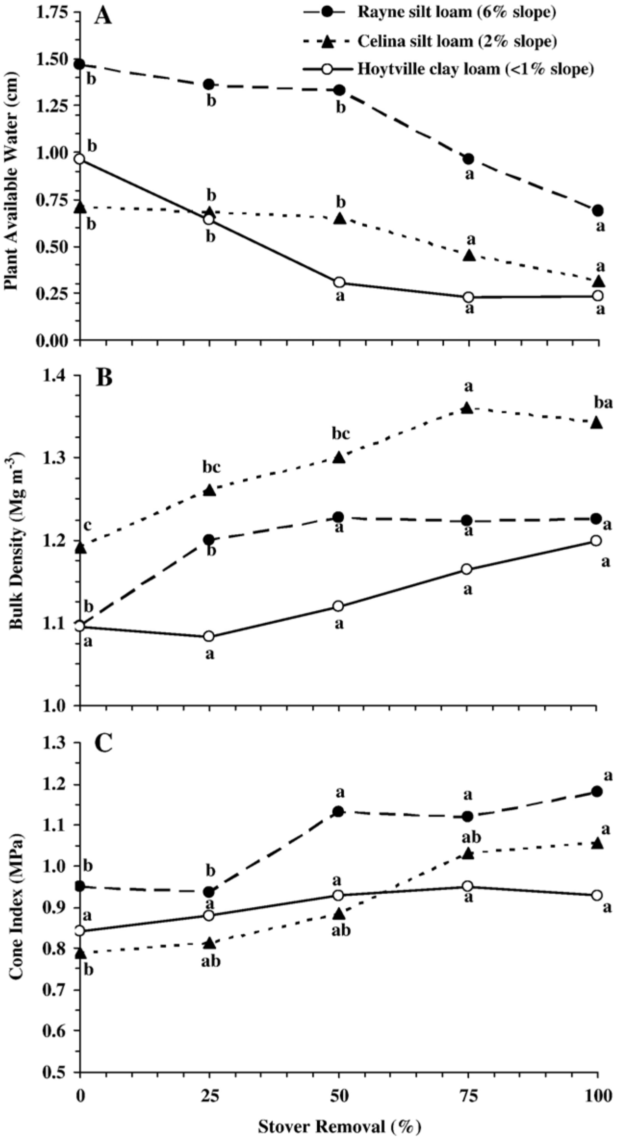

Fig. 4. Changes in A) plant available water, B) bulk density, and C) cone index due to stover removal at 0, 25, 50, 75, and 100% from three contrasting soils under long-term (>8 yr) NT management. Means followed by the same letters are not significantly different within the same soil.

3.4. Crop yields

Stover removal reduced grain (Fig. 5A) and stover (Fig. 5B) yields on RSL but not on CSL and HCL. In RSL, grain and stover yields decreased linearly with increase in rate of stover removal. The 25% rate of stover removal did not significantly reduce crop yields, but removal at higher rates had a dramatic effect on grain yield. Removal of 50% and 75% of stover reduced grain yield by an average of 1.95 Mg ha^{-1}, while complete stover removal reduced it by 3.32 Mg ha^{-1}. Stover removal more adversely affected grain than stover yield. Complete stover removal reduced stover yield by 1.59 Mg ha^{-1}. The average corn yield across the five stover removal treatments was 11.65 Mg ha^{-1} for grain and 7.86 Mg ha^{-1} for stover in CSL, and 10.05 Mg ha^{-1} for grain and 7.45 Mg ha^{-1} for stover in HCL (Fig. 5A–B).

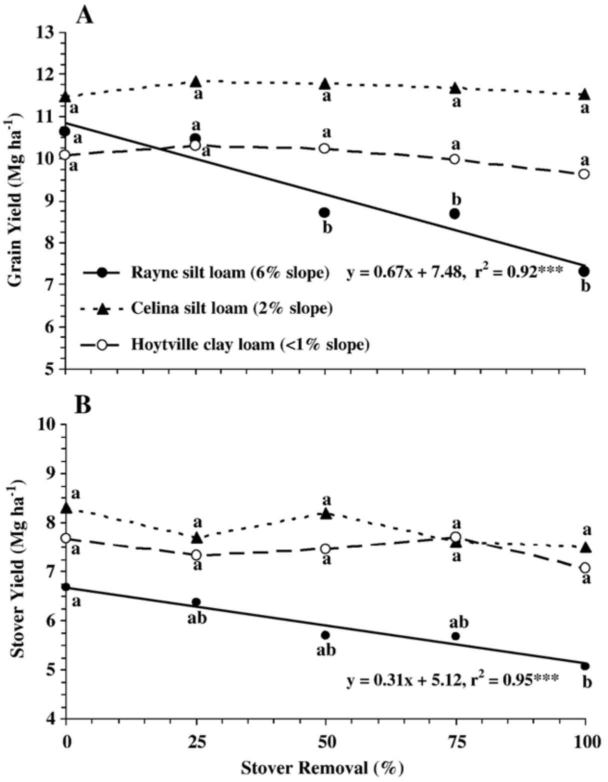

Fig. 5. Yields of A) corn grain and B) stover in response to stover removal at 0, 25, 50, 75, and 100% from three NT soils. Means followed by the same letters are not significantly different within the same soil. The correlations for the Rayne silt loam were all significant at the 0.001 (***) probability level.

The decrease in corn yields in RSL was attributed to decrease in PAW, abrupt fluctuations in soil temperature, and moderate increase in soil compaction due to stover removal. Wetter and colder conditions during spring in soils receiving stover mulch ≥75% slightly delays corn emergence. Corn plants were significantly taller under complete stover removal than those in plots receiving stover mulch ≥75% during the first one-half month after emergence. Trends in plant height were, however, reversed later in the growing season.

Changes in soil temperature due to stover removal most likely contributed to differences in corn growth and yield in RSL. The daytime maximum soil temperature measured at 5-cm depth increased with increase in rate of stover removal for the three soils (Table 3). Mean daytime soil temperature for the RSL was 23.6±0.5 °C in soils with 0%, 25.6±0.7 °C with 25%, 27.4±0.8 °C with 50%, 29.4±0.7 °C with 75%, and 30.7±0.5 °C with 100% of stover removed. These results show that complete stover removal increased soil temperature by an average of about 6 °C for the RSL. Corn grain yield was negatively ($r = -0.50$; $P < 0.05$) correlated with soil temperature. The lower temperature in soils mulched with ≥75% of stover delayed emergence but improved corn growth later in the season. Multiple regression analyses showed that increase in soil compaction level and fluctuations in temperature explained 44% of the decrease in grain yield (Grain = 25.2–5.94 Cone index — 0.32 Temperature; $P < 0.05$), whereas increase in PAW explained 34% of the increase in stover yield (Stover = 3.27 + 13.58 PAW; $P < 0.05$). The large and significant effects of stover removal on PAW and soil temperature but not on crop yields in CSL and HCL suggests the confounding and interactive effects of a multitude of factors determining crop yields.

This study reveals that changes in SOC, soil physical properties, and crop yields due to stover removal were most significant under complete removal. Because results under the lowest removal rate (25%) were not significantly different from not removing stover, a partial removal of stover may be feasible in some soils. Based on our preliminary results, we suggest that 25% may be the threshold removal rate from erosion-prone soils. However, logistics of harvesting stover by 25% need a careful and an objective consideration. Removal of only 25% of stover may neither be economically feasible nor sufficient to produce high volumes of ethanol needed to ease dependence on fossil fuels.

4. Conclusions

This study shows that rates of SOC sequestration, compaction levels, and water and temperature regimes near the soil surface are negatively affected when stover is removed from long-term NT continuous corn over a short period of 2 1/2 years. Stover removal at rates >25% strongly reduced SOC, decreased earthworm population, increased soil strength, reduced PAW, and decreased crop yields. However; the rate and magnitude of undesirable impacts depended strongly on site-specific characteristics (e.g., soil texture, drainage, topography). Unfavorable effects of stover removal were more pronounced on an unglaciated, sloping, well drained, and erosion-prone soil than on a glaciated and poorly drained clayey soil developed on nearly level terrain. Clayey soils with high shrink–swell potential and poor drainage and nearly level silt loam soils may respond to stover removal over a time horizon of longer than 2 1/2 years. Our results highlight the urgent need for determining site-specific threshold levels of the rate of stover removal for principal soils across the U.S. Corn Belt region. We acknowledge that while this short-term study shows significant impacts of corn stover removal on soil properties, SOC, CO_2 emission, and crop yields, further monitoring of these impacts over a long time period (>2 1/2 yr) are warranted to ascertain the threshold levels of stover removal and make robust recommendations of the implications of stover removal. Finally, this study on fairly small plots should be replicated in larger plots or field-scale experiments to get a better understanding of the effects of stover removal on soil and ecosystem function.

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