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Long-term impacts of residue harvesting on soil quality

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ABSTRACT

Development of the cellulosic bioenergy industry raises the prospect of wide spread stover harvesting in the near future; however, the impact of stover harvesting on soil quality may not be apparent for several years. Here we evaluate the impact of 19 years of either zero or approximately 90% removal of above ground crop residue on soil quality. The 0–5, 5–15, and 15–30 cm soil depths of Waukegan silt loam (Typic Hapludoll) from east-central Minnesota were sampled from plots after 12 and 7 years of maize and soybean cropping, respectively. On average for the 0–5 and 5–15 cm depths, soil organic C was 12% less, total N was 12.6% less, N mineralization potential was 27.7% less, cation exchange capacity was 7.3% less, macro aggregation was 13.0% less, and total respiration was 12.3% less for plots with residue harvesting relative to plots where residue was not harvested. Minimal impacts of residue harvesting were apparent for the 15–30 cm soil samples, except N mineralization potential which was 28% lower for plots with residue harvesting. Declines in soil quality indicators due to residue harvesting were only slightly less severe for no-tillage plots relative to chisel and moldboard plow tillage plots. We conclude that harvesting 90% of above ground residue for 19 years resulted in substantial degradation of soil quality, and that the impact on N mineralization potential was substantially larger than the loss of total N, suggesting that labile organic N was selectively depleted. We also conclude that stover harvesting for bioenergy production could cause similar degradation of soil quality unless management practices that increase C inputs to soils are also implemented.

1. Introduction

Corn stover is estimated to comprise 20–30% of the cellulosic feedstock (Perlack et al., 2005; Graham et al., 2007; US Department of Energy, 2011) that will be needed to meet the renewable fuel standard of 36 billion gallons of biofuel production by the year 2022, which is required by the Energy Independence and Security Act of 2007. The development of a cellulosic biofuel industry, if implemented correctly, is an opportunity to increase energy security and reduce net greenhouse gas emissions without exacerbating competition between food and fuel production. Industrial scale harvesting of biomass for bioenergy production, however, does present potential environmental risks. In particular, soil scientists have expressed concerns that the long-term harvesting of biomass for bioenergy production will have an adverse impact on soil quality and agricultural productivity (Wilhelm et al., 2004, 2007; Lal, 2004; Lal and Pimentel, 2007; Robertson et al., 2008; Hammerbeck et al., 2012; Stetson et al., 2012).

Surface residues increase both infiltration and the retention of water on the soil surface thereby reducing surface run off following a storm event. Hence, leaving enough residues to cover the soil surface is one of the most effective agricultural management strategies for decreasing soil erosion (Gilley et al., 1986). Surface residues also influence the radiation balance, and thereby buffer surface soil temperatures and decrease water loss to evaporation. These processes increase soil moisture levels, which is generally beneficial for crop growth but can delay planting and increase denitrification during a wet spring (Thomas et al., 2011). Residues, whether on the surface or incorporated by tillage, are the primary substrate for microorganisms, earthworms and other soil fauna. The biologically mediated mineralization of residue releases humic monomers to the soil solution that subsequently form new soil organic matter (humus) through heteropolymerization and/or aggregation (Stevenson, 1982; Piccolo, 2001; Simpson, 2002).

Soil organic matter contributes to soil quality and agricultural productivity through numerous physical, chemical, and biological processes. Organic matter enhances stabilization of soil structure (Tisdall and Oades, 1982; Hammerbeck et al., 2012), which increases aeration, drainage, and water holding capacity and decreases penetration resistance providing a better rooting environment for plants. Soil organic matter also contributes to

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cation exchange capacity, pH buffering capacity, and is a reservoir for plant nutrients that are released during microbially mediated nutrient cycling (Tisdall et al., 1986). Although difficult to quantify, most reports indicate that mineralization of soil organic matter is a major source of the N utilized by plants. For example, in a well controlled and well fertilized ^{15}N greenhouse pot study, soil organic matter mineralization supplied between 41.4 and 57.7% of the total N utilized by maize plants (Lü et al., 2012). Globally fertilizer N use efficiency in crop production is only about 33% (Raun and Johnson, 1999). Thus serving as a reservoir for N and other plant nutrients and slowly releasing those nutrients to a crop through mineralization is a critical function of soil organic matter.

Whether the amount of soil organic matter is increasing, decreasing, or staying constant in a soil is determined by the balance between the rate of residue input the efficiency of the residue decomposition-humification process, and the rate of mineralization of the existing soil organic matter. Harvesting of crop residues for bioenergy production necessarily implies a lowering of the rate of input of residue to the soil, which will lead to a decrease in soil organic matter levels, soil fertility and ultimately productivity (Johnson et al., 2006), unless other mitigating management practices are implemented. Evidence of the impact of residue harvesting on crop yields, however, is inconsistent (Karlen et al., 2011a); some studies have shown decreased yields in years following residue harvesting (Wilhelm et al., 1986; Linden et al., 2000) while other studies have reported no loss of yield or even yield increases (Karlen et al., 1984, 2011b; Kaspar et al., 1990). The variable impact of residue harvesting on yields attests to the complex nature of residue-microbiology-soil-climate-crop interactions and to the slow rate of change in levels of the soil organic matter in response to management. Because crop yields are governed by numerous interactions, short-term changes in crop yields are not a good indicator of the long-term impact of a management system on soil quality. Careful analysis of changes in soil quality in well managed long-term plots is a far more reliable means of assessing the impacts of management on soil quality.

The long-term nitrogen, tillage, and residue management plots (NTRM plots) on the University of Minnesota Agricultural Experimental Station near Rosemont, MN were used for this investigation. The data reported here were originally part of an investigation on the influence of moisture on near-infrared reflectance spectroscopy (NIRS) and the ability of NIRS-partial least squares regression analysis to predict measured soil properties (Chang et al., 2005). Given current interest in bioenergy, we have reanalyzed the data to assess the impact of residue removal on several soil quality indicators.

Several previous reports have focused on changes in soil organic C (SOC) stocks and crop yields on the NTRM plots (Linden et al., 2000; Clapp et al., 2000; Allmaras et al., 2004; Dolan et al., 2006). After 13 years of cropping following pasture, stover harvesting decreased 0–15 cm SOC stocks in annually tilled (both chisel and moldboard plowed) plots, however, stover harvest had no apparent effect on the 15–30 cm SOC stocks (Clapp et al., 2000). In the no-till plots, the 0–15 cm SOC stocks were nearly unchanged with stover harvesting and increased by 14% with stover return (Clapp et al., 2000). By contrast, the 15–30 cm SOC stocks decreased with time under no-till, while showing no consistent trends in the tilled plots. Analysis of changes in δ^{13}C values with time indicated a 35% decline in corn stover derived SOC due to stover harvesting (Allmaras et al., 2004). In a follow-up study after 23 years, Dolan et al. (2006) reported that stover harvesting significantly reduced both SOC and N stocks relative to residue returned treatments for most depth increments and in the whole soil profile (0–5 cm). They reported differences between residue harvesting and no-residue harvesting treatments of 2, 20, and 9 Mg–C ha^{-1} and 0.1, 0.8, and 0.2 Mg–N ha^{-1} for the no-till, chisel, and moldboard treatments, respectively. These results from prior studies indicate the dynamic nature of SOC and N stocks in the Waukegan soil and the long time that may be required to produce measurable changes in soil quality parameters due to residue harvesting.

In the present study, we report the impact of long-term stover harvesting on various soil quality indicators for the Waukegan soil. Given the emerging cellulosic bioenergy industry and the potential for large scale harvesting of crop residues we believe it is essential to consider the implications of residue harvesting on soil quality using data from long-term plots. In the future, recently established residue harvesting studies (Karlen et al., 2011a) that are specifically designed to explore the implications of the emerging bioenergy industry will undoubtedly provide a rich source of information on the potential impacts of biomass harvesting on soil quality and agricultural productivity.

2. Materials and methods

2.1. Research plots

The NTRM plots were established in 1980 on the University of Minnesota Outreach, Research and Education Experiment Station near Rosemont MN (latitude 44°42′ 59″ N, longitude 93°05′ 59″ W). Maize was grown on the plots from 1980 through 1992, and soybeans were grown from 1993 through 1998. Tillage treatments included, fall moldboard plow tillage with spring disking (plow); fall chisel tillage with spring disking (chisel), and no-tillage (no-till). Residue management included removal of approximately 90% of above ground residue for all tillage systems, incorporation of residue for the plow and chisel systems, and leaving the residue on the surface for the no-tillage system. A “surface” residue treatment was also practiced for the plow and chisel tillage systems, which involved removal of the above ground residue prior to fall tillage, and subsequent replacement of chopped residue back on the surface after tillage. These plots were not used in the present study, due to concerns that the returned surface residue may have partially blown off of the plots. Nitrogen fertilizer ($(NH_4)_2SO_4$) application rates for the first three years were 0, 200, and 200 s kg ha^{-1} (the s indicates a split application with 100 kg ha^{-1} preplant and 100 kg ha^{-1} sidedressed). From 1983 through 1992 (ten years) N management was 0, 100, and 200 kg ha^{-1}. Agricultural lime was applied in 1985 and again in 1987 on some of the plots receiving 100 and 200 kg ha^{-1} N applications. No nitrogen fertilizer was applied during soybean years. The overall experimental design (Clapp et al., 2000) consisted of eight tillage by residue treatments randomly assigned to 18 × 50 m block. Each block was subdivided into 12 plots which were each assigned one of three fertilizer treatments.

2.2. Soil samples

The soils on the nearly level (<1% slope) NTRM plots are classified as a Waukegan silt loam (fine-silty over skeletal, mixed, superactive, mesic Typic Hapludoll). Soil sampling occurred after 19 years of plot management. A total of 37 plots were sampled for the original study (Chang et al., 2005), however, for this study only 28 plots representing 6 of the treatments were included, because of the previously mentioned concerns about the integrity of the surface-chisel and surface-plow treatments. In addition, two locations within alleyways between plots, which had been maintained in a fallow condition for 19 years, and two locations in adjacent grass boarder strips, which had been in sod for 19 years, were sampled. Three soil samples were collected from each location, representing the 0–5, 5–15, and 15–30 cm depth increments. Care was taken to remove crop residue and coarse roots from the samples before analysis. As the samples were collected in early May before planting or fertilization there were few live roots in the cultivated and fallow plots. No attempt was made to remove fine roots from the sod samples.

2.3. Measurement of soil properties

Total C and N were determined by dry combustion using a Carlo Erba NA 1500 NSC elemental analyzer (Maake Buchler Instruments, Paterson, NJ). For the analysis, air-dried soils were crushed to pass through a 2 mm sieve, and then ground using an agate mortar. The pH of the sampled soils in 1:2.5 soil-$CaCl_2$ suspensions ranged from 3.74 to 6.65, hence total C was assumed to equal organic C. Cation exchange capacity was measured by the pH 7 NH_4OAc method (US Department of Agriculture, 1996). The particle size distribution was analyzed using the pipette method (Walter et al., 1978) for 18 representative soil samples (six for each depth interval). Potentially mineralizable N was assessed based on NH_4 production during 7 d anaerobic incubations at 40 °C (Keeney, 1982). Total and basal respiration were determined based on 35 d incubations at 25 °C (Drinkwater et al., 1996). The weight percentage of soil aggregates retained on 4, 2, 1, 0.5, and 0.25 mm sieves was measured by the wet sieving technique using samples that had been stored field moist at 4 °C before the analysis (Kemper and Rosenau, 1986). Both maccroaggregation (sum of mass percentages of aggregates >0.25 mm) and geometric mean diameter ($\mathrm{GMD} = \exp\left[\sum_{i=1}^{n} w_i \log x_i / \sum_{i=1}^{n} w_i\right]$; where x_i is the average diameter and w_i is the weight of aggregates for size class i) were used as metrics to assess aggregation. Soil moisture for both field moist samples and air-dried subsamples (about 1 g) was determined gravimetrically relative to the oven dry weight (105 °C for 12 h). Only the air-dry moisture contents are reported here.

2.4. Statistical analysis

Analysis of variance (ANOVA) conducted using SAS 9.2 included main effects for depth, nitrogen, tillage, residue, and lime and interactions for depth*tillage and depth*residue. Depth by residue and depth by tillage interactions were statistically significant ($\alpha = 0.05$) for most soil quality indicators whereas other interactions were generally not significant and therefore were excluded from the ANOVA model. Significant differences between means for residue removed versus residue not removed and grass versus fallow treatments are based on t tests. For the t tests, N fertilizer and lime treatments were pooled to provide either 4 or 5 replications for each residue by tillage by depth treatment. Samples collected from the fallow alleyway and grass strips were not included in the ANOVA, but were compared using a t test with 2 degrees of freedom.

3. Results and discussion

3.1. Residue removal impact on soil quality

The ANOVA documenting the overall impact of 19 years of removing ~90% of the above ground residue on various soil quality parameters is documented in Table 1 for the NTRM plots near Rosemont, Minnesota. Depth was highly significant ($P < 0.0001$) for all of the studied soil properties. Residue removal was also highly significant for all dependent variables except pH, total respiration, and basal respiration. Tillage was significant ($P < 0.05$) for all soil properties except total C, total N, pH and air-dried water content. By contrast, N fertilization treatments and lime applications only significantly ($P < 0.05$) influenced soil pH. The depth by tillage interaction was significant ($P < 0.05$) for all soil quality indicators except CEC, macro aggregation, and air-dry water content. The depth by residue interactions was significant ($P < 0.05$) for total C, total N, N-mineralization potential, CEC, and air-dried water content. The ANOVA results demonstrate that depth, tillage and residue management were the dominant independent variables and hence justify pooling replications for the t tests across nitrogen and lime treatments for all soil quality indicators with the possible exception of pH.

3.2. Impact of residue removal on soil organic carbon

The results indicate that residue removal had a substantial impact on levels of soil organic C (OC). Although variability was relatively high for OC among the no-till samples, residue removal resulted in a marginally significant ($P < 0.10$) 18.5% loss of OC for the surface soil (0–5 cm depth). No effect of residue removal was apparent for the 5–15 and 15–30 cm depths in the no-till samples. By contrast, residue removal resulted in highly significant ($P < 0.01$) losses of OC ranging from 9.45 to 16.48% for both the 0–5 and 5–15 cm depths but no apparent effect for the 15–30 cm depth in the chisel and plow tillage systems. Soil OC levels in the 0–5 cm soil for the continuous grass strips was 40.0 g kg^{-1}, which compares with 31.7 g kg^{-1} in the no-till, 29.5 g kg^{-1} in the chisel, and 27.1 g kg^{-1} in the plow tillage 0–5 cm soil samples when residue was left on the surface or incorporated. By contrast, there was little difference in average OC levels for the 0–5 cm depth soil samples regardless of fallow, plow, chisel, or no-till (23.8, 24.5, 24.7, 25.8 g kg^{-1}, respectively) when residue was removed. The results demonstrate the critical importance of residues in maintaining soil OC levels regardless of management system.

Assuming a uniform bulk density of 1.3 g cm^{-3} for all systems, total OC difference between the residue removed and residue returned systems to 15 cm depth were 4.7, 7.2, and 6.9 Mg Ha^{-1} for the no-till, chisel, and plow systems, respectively. Soil bulk density is influenced by management and varies seasonally; hence the above estimates of OC differences between treatments are more accurately described as differences in organic C

Table 1
Results for ANOVA showing the probability of greater F for independent variables (depth, nitrogen fertilization, tillage system, residue removal, and lime application) on various dependent variables including total carbon (C), total N (N), nitrogen mineralization potential (Nmin), cation exchange capacity (CEC), soil pH (pH), percent macro aggregates (Agg), aggregate geometric mean weight diameter (GMD), basal respiration (Bresp), total respiration (Tresp), and air-dried water content (Water).

Soil property	C	N	Nmin	CEC	pH	Agg	GMD	Bresp	Tresp	Water
Depth	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Nitrogen	0.19	0.055	0.062	0.74	0.001	0.44	0.20	0.48	0.31	0.85
Tillage	0.51	0.46	0.048	0.029	0.25	<0.0001	<0.0001	<0.0001	<0.0001	0.93
Residue	<0.0001	<0.0001	<0.0001	<0.0001	0.56	<0.0001	<0.0001	0.74	0.38	0.0003
Lime	0.39	0.43	0.50	0.55	0.006	0.96	0.26	0.46	0.27	0.72
Depth*Tillage	0.002	0.0001	0.008	0.28	<0.0001	0.085	0.003	0.011	0.003	0.97
Depth*Residue	0.0007	0.0007	0.012	0.0001	0.19	0.073	0.075	0.18	0.087	<0.0001

Table 2
Comparisons of the effect of leaving residue (*Incorporated* for chisel and plow tillage and *Surface* for no-tillage) versus removing residue (*Removed*) on various soil properties, including total C, total N, nitrogen mineralization potential, cation exchange capacity, soil pH, percent macro-aggregates, aggregate geometric mean weight diameter, basal respiration, total respiration, and air-dried water content. Statistical significance for comparisons between means for residue removed versus not removed are indicated by stars.

Total carbon

No-till depth (cm)	Surface (g-C/kg)	Removed (g-C/kg)	Change (%)	t (df = 8)	Significance
0–5	31.72	25.84	−18.54	1.73	$P < 0.100$
5–15	26.66	26.00	−2.48	0.94	N.S.
15–30	19.58	20.50	4.70	−0.98	N.S.
Chisel depth (cm)	Incorporated (g-C/kg)	Removed (g-C/kg)	Change (%)	t (df = 7)	Significance
0–5	29.53	24.66	−16.48	6.71	$P < 0.010$
5–15	27.80	24.72	−11.08	4.23	$P < 0.010$
15–30	20.33	20.36	0.17	−0.03	N.S.
Plow depth (cm)	Incorporated (g-C/kg)	Removed (g-C/kg)	Change (%)	t (df = 7)	Significance
0–5	27.10	24.54	−9.45	3.31	$P < 0.010$
5–15	27.18	23.16	−14.77	4.00	$P < 0.010$
15–30	23.15	22.56	−2.55	0.48	N.S.
Control depth (cm)	Grass (g-C/kg)	Fallow (g-C/kg)	Change (%)	t (df = 2)	Significance
0–5	40.00	23.75	−40.63	12.68	$P < 0.010$
5–15	24.65	22.30	−9.53	1.17	N.S.
15–30	17.75	16.70	−5.92	0.84	N.S.

Nitrogen mineralizaton potential

No-till depth (cm)	Surface (mg-N/kg)	Removed (mg-N/kg)	Change (%)	t (df = 8)	Significance
0–5	75.42	37.75	−49.94	2.08	$P < 0.05$
5–15	44.77	38.32	−14.42	1.29	N.S.
15–30	21.30	15.69	−26.32	2.63	$P < 0.025$
Chisel depth (cm)	Incorporated (mg-N/Kg)	Removed (mg-N/Kg)	Change (%)	t (df = 7)	Significance
0–5	73.22	53.75	−26.58	2.36	$P < 0.05$
5–15	49.56	36.29	−26.77	2.82	$P < 0.025$
15–30	22.79	15.46	−32.16	2.54	$P < 0.025$
Plow depth (cm)	Incorporated (mg-N/Kg)	Removed (mg-N/Kg)	Change (%)	t (df = 7)	Significance
0–5	47.33	33.77	−28.65	2.74	$P < 0.025$
5–15	40.60	32.45	−20.07	2.18	$P < 0.05$
15–30	28.19	21.00	−25.50	2.01	$P < 0.05$
Control depth (cm)	Grass (mg-N/Kg)	Fallow (mg-N/Kg)	Change (%)	t (df = 2)	Significance
0–5	184.96	56.11	−69.67	29.20	$P < 0.010$
5–15	88.28	31.39	−64.44	4.41	$P < 0.025$
15–30	24.40	5.74	−76.48	10.13	$P < 0.010$

pH

No-till depth (cm)	Surface (pH units)	Removed (pH units)	Change (%)	t (df = 8)	Significance
0–5	4.90	4.84	−1.14	0.12	N.S.
5–15	6.16	5.88	−4.58	2.88	$P < 0.025$
15–30	6.19	6.18	−0.19	0.15	N.S.
Chisel depth (cm)	Incorporated (pH units)	Removed (pH units)	Change (%)	t (df = 7)	Significance
0–5	5.35	5.39	0.78	−0.28	N.S.
5–15	6.00	5.82	−3.07	0.64	N.S.
15–30	6.18	6.20	0.44	−0.69	N.S.
Plow depth (cm)	Incorporated (pH units)	Removed (pH units)	Change (%)	t (df = 7)	Significance
0–5	5.40	5.60	3.69	−1.10	N.S.
5–15	5.88	5.78	−1.70	0.38	N.S.
15–30	5.89	5.90	0.10	−0.03	N.S.
Control depth (cm)	Grass (pH units)	Fallow (pH units)	Change (%)	t (df = 2)	Significance
0–5	5.66	5.79	2.21	−0.82	N.S.
5–15	5.95	5.89	−0.93	I.D.	N.S.
15–30	6.21	6.24	0.48	−0.45	N.S.

Macro aggregates

No-till depth (cm)	Surface (%)	Removed (%)	Change (%)	t (df = 8)	Significance
0–5	74.41	30.12	−59.52	8.33	$P < 0.010$
5–15	86.44	76.29	−11.73	5.18	$P < 0.010$
15–30	63.42	61.37	−3.22	0.67	N.S.
Chisel depth (cm)	Incorporated (%)	Removed (%)	Change (%)	t (df = 7)	Significance
0–5	31.75	27.42	−13.64	0.89	N.S.
5–15	74.29	62.38	−16.03	2.59	$P < 0.025$
15–30	57.21	49.87	−12.83	1.88	$P < 0.100$
Plow depth (cm)	Incorporated (%)	Removed (%)	Change (%)	t (df = 7)	Significance
0–5	28.14	36.67	30.33	−2.20	$P < 0.05$
5–15	63.24	58.57	−7.38	1.72	$P < 0.100$
15–30	53.62	50.57	−5.69	1.22	N.S.

Table 2 (*Continued*)

Macro aggregates

Control depth (cm)	Grass (%)	Fallow (%)	Change (%)	t ($df=2$)	Significance
0–5	86.79	11.13	−87.18	24.75	$P < 0.010$
5–15	84.07	72.99	−13.18	2.77	$P < 0.100$
15–30	57.32	49.85	−13.03	0.83	N.S.

Total respiration

No-till depth (cm)	Surface (mg-CO_2-C/kg/day)	Removed (mg-CO_2-C/kg/day)	Change (%)	t ($df=8$)	Significance
0–5	68.68	62.31	−9.28	0.64	N.S.
5–15	50.18	33.16	−33.91	2.81	$P < 0.025$
15–30	19.99	22.58	12.97	−0.41	N.S.

Chisel depth (cm)	Incorporated (mg-CO_2-C/kg/day)	Removed (mg-CO_2-C/kg/day)	Change (%)	t ($df=7$)	Significance
0–5	50.58	62.29	23.14	−1.58	$P < 0.100$
5–15	41.18	35.92	−12.77	0.67	N.S.
15–30	24.23	25.20	3.98	−0.15	N.S.

Plow depth (cm)	Incorporated (mg-CO_2-C/kg/day)	Removed (mg-CO_2-C/kg/day)	Change (%)	t ($df=7$)	Significance
0–5	41.93	27.67	−34.01	2.25	$P < 0.05$
5–15	36.62	34.02	−7.09	0.31	N.S.
15–30	15.73	27.07	72.10	−2.37	$P < 0.025$

Control depth (cm)	Grass (mg-CO_2-C/kg/day)	Fallow (mg-CO_2-C/kg/day)	Change (%)	t ($df=2$)	Significance
0–5	144.17	59.06	−59.03	25.64	$P < 0.010$
5–15	34.02	25.75	−24.32	I.D.	I.D.
15–30	28.91	21.06	−27.14	1.17	N.S.

Total nitrogen

No-till depth (cm)	Surface (g-N/kg)	Removed (g-N/kg)	Change (%)	t ($df=8$)	Significance
0–5	2.80	2.26	−19.29	1.72	$P < 0.100$
5–15	2.38	2.20	−7.56	2.72	$P < 0.010$
15–30	1.68	1.70	1.19	−0.23	N.S.

Chisel depth (cm)	Incorporated (g-N/kg)	Removed (g-N/kg)	Change (%)	t ($df=7$)	Significance
0–5	2.55	2.12	−16.86	6.07	$P < 0.010$
5–15	2.48	2.16	−12.73	4.41	$P < 0.010$
15–30	1.73	1.74	0.87	−0.11	N.S.

Plow depth (cm)	Incorporated (g-N/kg)	Removed (g-N/kg)	Change (%)	t ($df=7$)	Significance
0–5	2.28	2.10	−7.69	3.17	$P < 0.010$
5–15	2.33	2.06	−11.40	4.28	$P < 0.010$
15–30	1.98	1.98	0.25	−0.05	N.S.

Control depth (cm)	Grass (g-N/kg)	Fallow (g-N/kg)	Change (%)	t ($df=2$)	Significance
0–5	3.60	2.00	−44 44	13.86	$P < 0.010$
5–15	2.30	1.85	−19.57	3.06	$P < 0.05$
15–30	1.60	1.45	−9.38	1.64	N.S.

Cation exchange capacity

No-till depth (cm)	Surface (cmol/kg)	Removed (cmol/kg)	Change (%)	t ($df=8$)	Significance
0–5	21.89	20.13	−8.05	2.24	$P < 0.05$
5–15	23.04	22.33	−3.06	1.33	N.S.
15–30	19.45	20.69	6.37	−2.92	$P < 0.010$

Chisel depth (cm)	Incorporated (cmol/kg)	Removed (cmol/kg)	Change (%)	t ($df=7$)	Significance
0–5	22.36	19.48	−12.89	6.45	$P < 0.010$
5–15	22.43	20.86	−6.96	3.24	$P < 0.010$
15–30	20.30	19.21	−5.35	3.08	$P < 0.010$

Plow depth (cm)	Incorporated (cmol/kg)	Removed (cmol/kg)	Change (%)	t ($df=7$)	Significance
0–5	21.69	20.33	−6.24	2.60	$P < 0.025$
5–15	22.38	20.87	−6.78	3.11	$P < 0.010$
15–30	19.97	19.86	−0.56	0.23	N.S.

Control depth (cm)	Grass (cmol/kg)	Fallow (cmol/kg)	Change (%)	t ($df=2$)	Significance
0–5	24.40	20.34	−16.66	5.62	$P < 0.025$
5–15	21.67	21.35	−1.50	0.59	N.S.
15–30	19.60	18.52	−5.54	1.67	N.S.

Air-dried water content

No-till depth (cm)	Surface (%)	Removed (%)	Change (%)	t ($df=8$)	Significance
0–5	4.56	3.71	−18.53	1.88	$P < 0.100$
5–15	2.38	2.72	14.36	−3.62	$P < 0.010$
15–30	2.62	2.64	0.84	−0.49	N.S.

Chisel depth (cm)	Incorporated (%)	Removed (%)	Change (%)	t ($df=7$)	Significance
0–5	4.52	3.79	−16.24	10.32	$P < 0.010$
5–15	2.62	2.35	−9.98	3.23	$P < 0.010$
15–30	2.80	2.53	−9.49	6.91	$P < 0.010$

Table 2 (*Continued*)

Air-dried water content

Plow depth (cm)	Incorporated (%)	Removed (%)	Change (%)	t (df = 7)	Significance
0–5	4.30	3.93	−8.41	5.29	$P < 0.010$
5–15	2.45	2.56	4.68	−2.17	$P < 0.05$
15–30	2.78	2.61	−6.04	2.16	$P < 0.05$

Control depth (cm)	Grass (%)	Fallow (%)	Change (%)	t (df = 2)	Significance
0–5	4.44	3.63	−18.24	6.67	$P < 0.025$
5–15	2.50	2.52	1.00	−0.33	N.S.
15–30	2.66	2.52	−5.08	0.70	N.S.

Aggregate geometric mean diameter

No-till depth (cm)	Surface (mm)	Removed (mm)	Change (%)	t (df = 8)	Significance
0–5	0.98	0.51	−48.57	5.06	$P < 0.010$
5–15	1.37	1.03	−24.69	5.53	$P < 0.010$
15–30	0.88	0.78	−10.89	2.64	$P < 0.025$

Chisel depth (cm)	Incorporated (mm)	Removed (mm)	Change (%)	t (df = 7)	Significance
0–5	0.51	0.50	−2.35	0.55	N.S.
5–15	1.04	0.85	−17.98	2.15	$P < 0.05$
15–30	0.76	0.70	−8.04	1.48	$P < 0.100$

Plow depth (cm)	Incorporated (mm)	Removed (mm)	Change (%)	t (df = 7)	Significance
0–5	0.48	0.52	8.00	−1.75	$P < 0.100$
5–15	0.84	0.83	−1.55	0.24	N.S.
15–30	0.79	0.76	−4.05	0.82	N.S.

Control depth (cm)	Grass (mm)	Fallow (mm)	Change (%)	t (df = 2)	Significance
0–5	0.93	0.88	−5.46	0.12	N.S.
5–15	1.18	0.69	−41.85	1.55	N.S.
15–30	0.71	1.21	69.34	−3.01	$P < 0.05$

Basal respiration

No-till depth (cm)	Surface (mg-CO$_2$-C/kg/day)	Removed (mg-CO$_2$-C/kg/day)	Change (%)	t (df = 8)	Significance
0–5	55.94	46.88	−16.19	0.79	N.S.
5–15	36.93	22.47	−39.14	2.42	$P < 0.025$
15–30	11.29	19.14	69.47	−1.58	$P < 0.100$

Chisel depth (cm)	Incorporated (mg-CO$_2$-C/kg/day)	Removed (mg-CO$_2$-C/kg/day)	Change (%)	t (df = 7)	Significance
0–5	32.79	47.96	46.24	−2.06	$P < 0.05$
5–15	21.45	23.56	9.85	−0.38	N.S.
15–30	19.56	18.81	−3.81	0.10	N.S.

Plow depth (cm)	Incorporated (mg-CO$_2$-C/kg/day)	Removed (mg-CO$_2$-C/kg/day)	Change (%)	t (df = 7)	Significance
0–5	26.69	14.99	−43.81	2.01	$P < 0.05$
5–15	21.44	22.54	5.14	−0.14	N.S.
15–30	7.85	17.63	124.64	−3.49	$P < 0.05$

Control depth (cm)	Grass (mg-CO$_2$-C/kg/day)	Fallow (mg-CO$_2$-C/kg/day)	Change (%)	t (df = 2)	Significance
0–5	112.22	42.90	−61.77	13.39	$P < 0.010$
5–15	26.12	16.97	−35.03	I.D.	I.D.
15–30	15.30	13.66	−10.72	0.21	N.S.

I.D. = insufficient data; N.S. = not significant.

between in the upper 1,950,000 kg of soil per Ha rather than in the upper 15 cm of soil per Ha. Our results may be compared with those of Clapp et al. (2000) who reported that SOC stocks decreased in the 0–15 cm depth between year 0 and year 13 by 2.2, 5.7, and 5.6 Mg Ha^{-1} as a consequence of residue removal when averaged over N fertilizer treatments. In year 13, differences in SOC stocks (0–15 cm) between the residue removed and residue returned plots for the no-till, chisel, and plow tillage systems averaged over N fertilizer treatments were 3.0, 8.8, and 1.6 Mg Ha^{-1}, respectively. Our results for year 19 on the same plots are generally consistent with those of (Clapp et al., 2000), but suggest that the difference in SOC between the residue removed and residue returned plots continued to widen for the no-till and plow tillage systems. As noted by Dolan et al. (2006), it is important to analyze the full soil profile when evaluating changes in SOC stocks as different tillage systems can redistribute SOC in the soil profile. We only sampled to 30 cm and did not measure bulk density; here we assumed a uniform bulk density of 1.3 g cm^{-3} in order to compare our results with the previously published literature. Our primary interest is in assessing the legacy of residue harvesting on changes in soil quality.

3.3. Impact of residue harvesting on total and mineralizable nitrogen

In our study, the pattern of change in total N due to tillage, depth and residue removal was similar to that observed for SOC (Tables 1 and 2). No-tillage had a high percentage loss (−19.29%) in total N in the 0–5 cm depth, a smaller loss for the 5–15 cm depth (−7.56%) and no apparent change in total N for the 15–30 cm depth due to residue removal. By contrast, N losses for the chisel and plow tillage systems due to residue removal were distributed through the 0–5 and 5–15 cm depths with no apparent N loss for the 15–30 cm depth. Cumulative N losses for the upper 1,950,000 kg-soil Ha^{-1} (approximately 0–15 cm depth) due to 19 years of residue removal were 585, 689, and 458 kg-N Ha^{-1}, respectively, for the no-till, chisel, and plow systems when compared within tillage systems. Average difference in total soil N between the residue removed plots and the continuous grass strips were 1001, 1144, 1287, and 1625 kg-N Ha^{-1} for the no-till, chisel, plow and fallow systems, respectively.

The decrease in total N due to residue removal was only observed in the 0–5 and 5–15 cm soils samples and ranged from 7.56 to 19.29% whereas N mineralization potential decreased by 14.42 to 49.94% due to residue removal with the average decrease of 27.82% over all depths and all tillage systems (Table 2). The N mineralization potential for soil from the fallow strip was 64.44 to 76.48% lower than for the continuous grass soil samples. All of these changes in N mineralization potential were significant ($P < 0.05$) with the exception of the no-till 5–15 cm depth samples. The large percentage losses of N mineralization potential and the relatively smaller losses in percentages of total N suggest that easily mineralizable N was selectively lost from the soils as a legacy of 19 years of residue removal. Again assuming a bulk density of 1.3 g cm^{-3}, the loss of potentially mineralizable N summed over 0–30 cm depth are equivalent to 44, 44, and 34 kg-N Ha^{-1}, respectively, for the no-till, chisel, and plow tillage systems when comparing within a tillage system. When compared to the continuous grass external control, losses of potentially mineralizable N were 178, 170, 177, and 194 kg-N Ha^{-1} for the no-till, chisel, plow and fallow systems, respectively. Interestingly, the decreases in N mineralization potential were comparable on a percentage bases in the 15–30 cm depth samples to the values for the 0–5 and 5–15 cm depth samples. Most differences in other soil quality parameters were not significant for the 15–30 cm depth samples. Relating results of a 7-day anaerobic laboratory incubation to the ability of a soil to supply N through mineralization to a maize crop over the course of an entire growing season is problematic. None-the-less, these losses of potentially mineralizable N strongly suggest that farmers harvesting maize stover for bioenergy production for extended periods of time will have to increase N fertilization rates to have an equivalent supply of N fertility for the growing crop.

Stover harvesting removes a significant amount of N from soils. Karlen et al. (2011a) reported a five years average removal rate of 29.3 kg-N Ha^{-1} per year with residue harvesting in continuous corn. Yet several studies have reported comparable yields or even increased yields following residue removal (Karlen et al., 1984, 2011b; Kaspar et al., 1990). The ability to produce comparable or higher yields even as N is being removed from the system with residue harvesting and no increase in N fertilization suggests that the rate of N mineralization from the soil organic N pool had increased. The size of the organic N pool in soils is clearly finite; our results strongly suggest that 19 years of residue harvesting substantially depleted the liable organic N pool in the Waukegan soil.

3.4. Impact of residue harvesting on CEC, aggregation, basal respiration, and pH

Other notable changes in soil quality due to the legacy of residue harvesting are evident in Table 2. Cation exchange capacity decreased by 6.24 to 12.89% in the 0–5 cm depth samples. The water content of the air-dried 0–5 cm soil samples decreased by 8.41 to 18.53%. The percentage of macroaggregates decreased 59.52 and 13.64% in the no-till and chisel plow systems, and for unexplained reasons increase by 30.33% in the plow tillage system as a legacy of residue removal. The large loss of aggregate stability for the no-till system is of particular concern, as it suggests that the increased aggregate stability of surface soil under no-till is due to surface residue rather than an intrinsic property of no-tillage. This observation is consistent with that of Hammerbeck et al. (2012). Basal respiration and total respiration were generally lower for soil samples from plots where residue was removed, although there were inconsistencies in the results as total and basal respiration for the 0–5 cm depth of the chisel plow system appeared to increase with residue removal. The change in pH due to residue removal was generally not significant with the exception of the 5–15 cm depth for the no-tillage system. The lack of a pH response is probably due to the application of lime on some plots receiving high N fertilization and the fact that neither N-fertilization nor lime treatments were distinguished in the analysis shown in Table 2. pH was significantly influenced by both lime and N fertilization treatments in the ANOVA where these treatments were considered (Table 1).

4. Conclusions

Overall the results indicate a substantial degradation of soil quality as a legacy of 19 years of ~90% residue removal. The results also indicate selective loss of readily mineralizable organic N, which suggests that release of other nutrients (e.g., P and S) through mineralization of soil organic matter could also decline. The loss of cation exchange capacity indicates that long-term residue harvesting reduced the ability of the Waukegan soil to retain cationic nutrients. The plots in this study were on level (0–1%) slopes and hence had little risk of erosion. However, the observed decrease in percentage of maccroaggregates and aggregate mean weight diameter due to residue removal suggests that residue harvesting increased surface crusting, decreased infiltration, and increased surface runoff and erosion risk. Without compensating organic amendments or other conservation strategies, the long-term harvesting of crop residues degraded the quality of Waukegan soil.

Quantitative extrapolation of the observed degradation of quality for the Waukegan soil to other soils and management systems is not possible. However, qualitatively the same general trends may be anticipated. The results indicate that residue harvesting for bioenergy production with "business as usual" soil management is not sustainable. The first commercial cellulosic ethanol plants are currently under construction and several of these are targeting crop residues as primary feedstocks. The companies building these cellulosic biorefineries are well aware of the risk to soil quality posed by harvesting >90% of the above ground residue and are assuming responsibility for ensuring sustainability. Sustainability strategies may include corporate participation requirements that only 50% of the above ground residue is harvested in any one year and that fields be enrolled every 3rd (continuous corn) or 5th year (corn-soybean rotation). These strategies should cause substantially less degradation of soil quality than harvesting ~90% of above ground residue every year as was done in the present study. However, long-term data showing that such strategies are truly sustainable does not yet exist.

The results of our study suggest that no-tillage was slightly better than chisel or plow tillage. Soil quality under no-tillage, however, also clearly degraded with continuous residue harvesting. As the cellulosic bioenergy industry develops, new management systems that increase C inputs to soils will be needed to ensure sustainability. The use of cover crops, rotations that include deep rooted forage crops for part of the rotation, and greater use of organic amendments such as manure, sewage sludge, and biochar will be needed.

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