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Corn Stover Harvest, Tillage, and Cover Crop Effects on Soil Health Indicators

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Abstract

Monitoring soil health indicators (SHI) will help ensure that corn (*Zea mays* L.) stover harvest is sustainable. This study examines SHI changes after 5 yr of growing continuous corn with either chisel plow or no-tillage practices and harvesting 0, ~35, or ~60% of the stover. Two no-tillage treatments with a cereal rye (*Secale cereale* L.) cover crop and stover harvest rates of ~35 or ~60% were evaluated. All eight treatments were replicated four times in a randomized complete block design at an 11-ha site in Boone County, IA. Soil samples were collected following grain and stover harvest from 0- to 5- and 5- to 15-cm depth increments. Particulate organic matter C (POM-C) decreased when stover was removed or the soil was chisel plowed. No-till with 0% stover removal had 10 mg g^{-1} POM-C in the 0- to 5-cm soil layer, which was 1.9-fold higher than in other treatments. Potentially mineralizable N (PMN) was greater under cover crop treatments. Average PMN values were 56.9 and 45.5 μg g^{-1} PMN for no-till with cereal rye at 0- to 5- and 5- to 15-cm depths, respectively, compared with 17.5 and -3.7 μg g^{-1} PMN for the same no-till treatments without cereal rye. Other soil properties did not respond to increasing levels of stover removal. At this location and at the studied removal rates, 5 yr of harvesting corn stover did not decrease soil health, but POM-C data suggest that changes may be occurring. Long-term monitoring should continue to assess corn stover harvest sustainability.

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Monitoring soil health indicators (SHI) will help ensure that corn (*Zea mays* L.) stover harvest is sustainable. This study examines SHI changes after 5 yr of growing continuous corn with either chisel plow or no-tillage practices and harvesting 0, ~35, or ~60% of the stover. Two no-tillage treatments with a cereal rye (*Secale cereale* L.) cover crop and stover harvest rates of ~35 or ~60% were evaluated. All eight treatments were replicated four times in a randomized complete block design at an 11-ha site in Boone County, IA. Soil samples were collected following grain and stover harvest from 0- to 5- and 5- to 15-cm depth increments. Particulate organic matter C (POM-C) decreased when stover was removed or the soil was chisel plowed. No-till with 0% stover removal had 10 mg g^{-1} POM-C in the 0- to 5-cm soil layer, which was 1.9-fold higher than in other treatments. Potentially mineralizable N (PMN) was greater under cover crop treatments. Average PMN values were 56.9 and 45.5 μg g^{-1} PMN for no-till with cereal rye at 0- to 5- and 5- to 15-cm depths, respectively, compared with 17.5 and -3.7 μg g^{-1} PMN for the same no-till treatments without cereal rye. Other soil properties did not respond to increasing levels of stover removal. At this location and at the studied removal rates, 5 yr of harvesting corn stover did not decrease soil health, but POM-C data suggest that changes may be occurring. Long-term monitoring should continue to assess corn stover harvest sustainability.

Abbreviations: C0, chisel plow with no stover removal; MBC, microbial biomass C; NT0, no-till with no stover removal; NT35, no-till with moderate stover removal; NT60, no-till with high stover removal; NTR35, no-till with moderate stover removal and rye cover crop; NTR60, no-till with high stover removal and rye cover crop; PMN, potentially mineralizable N; POM-C, particulate organic matter C; POM-N, particulate organic matter N; SHI, soil health indicators; SMAF, Soil Management Assessment Framework; SOC, soil organic C.

Corn residues protect soils from the erosive forces of water and wind, maintain soil organic C (SOC) stocks, cycle essential plant nutrients, replenish the C that creates and sustains aggregation, and provide food and energy for the microbial community (Stetson et al., 2012; Ruis et al., 2017; Wilhelm et al., 2007, 2010). Removing an excessive amount of corn stover, defined as the harvested portion to distinguish it from residues left in the field, can result in soil degradation (Blanco-Canqui et al., 2014; Halvorson and Stewart, 2015; Moebius-Clune et al., 2008). However, without stover harvest, producers can encounter residue management problems with subsequent crops and therefore often increase their tillage intensity to reduce surface residues (Al-Kaisi et al., 2015; Sindelar et al., 2013; Swan et al., 1987).

A review of stover harvest literature suggests that 40% removal by mass (i.e., 60% remaining in the field) was an upper limit for maintaining SOC and preventing erosion (Ruis et al., 2017; Wilhelm et al., 2010). Johnson et al. (2014) concluded that the minimum average residue return required to sustain SOC is 5.7 ± 2.4 Mg ha^{-1} yr^{-1}, which could require 30 to 70% residue cover (Smith et al., 1990).

Core Ideas

- **In no-till continuous corn, cover crops increased potentially mineralizable N.**
- **Particulate organic matter C responded to tillage and residue removal at 0 to 5 cm.**
- **Stover removal for 5 yr negatively affected 2 of 12 measured soil properties.**

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Fields producing higher yields may provide more available stover for removal while still returning sufficient residue for soil resource protection (Karlen and Huggins, 2014). Current guidelines suggest that stover can be removed when corn grain yields are above 11 Mg ha^{-1} (15.5% moisture) (Owens et al., 2016).

Multiple studies from U.S. corn-growing regions have documented poorer soil physical and biological properties when stover was removed, especially when removal rates were high (>40%). The negative effect was site-specific and more pronounced in drier areas such as western Minnesota and South Dakota and non-irrigated sites in Nebraska (Supplemental Table S1). Stover harvest reduced soil organic matter by 10% (Barber, 1979; Blanco-Canqui et al., 2014; Halvorson and Stewart, 2015; Jin et al., 2015; Moebius-Clune et al., 2008; Stetson et al., 2012). Particulate organic matter was reduced by 40% compared with soils with no residue removal (Jin et al., 2015). Similarly, aggregate stability was reduced between 10 and 30% (Hammerbeck et al., 2012; Jin et al., 2015; Johnson et al., 2016; Karlen et al., 1994; Moebius-Clune et al., 2008; Stetson et al., 2012), but the erodible fraction increased by 1.2- to 6.5-fold in South Dakota, Minnesota, and Nebraska (Blanco-Canqui et al., 2014; Hammerbeck et al., 2012; Johnson et al., 2016; Osborne et al., 2014) because of stover harvest. Soil respiration was 5.5-fold higher when stover was returned than with complete removal (Karlen et al., 1994).

Tillage practices can cause greater changes in soil properties than stover removal alone (Wilhelm et al., 2007). In New York, stover removal reduced water-stable aggregates in both no-till and moldboard plowed soils. The moldboard plow soils had less than half the water-stable aggregates compared with the no-till soils (Moebius-Clune et al., 2008). Moldboard plow soils without stover removal had 19% lower soil organic matter than no-till soils with complete stover removal (Moebius-Clune et al., 2008). Less intensive tillage, such as chisel plowing, had intermediate effects on soil properties when combined with stover removal. In an Illinois study, Villamil and Nafziger (2015) found that soil C was not reduced across all chisel plow and no-till treatments as stover removal increased. Similarly, chisel plowing without stover removal resulted in similar stable aggregate mean weight diameters and erodible fractions compared with no-till soils and stover removal in Minnesota (Johnson et al., 2016).

Cover crops may help offset some of the soil risks posed by removing higher stover quantities (Blanco-Canqui et al., 2014; Bonner et al., 2014; Moore et al., 2014; Osborne et al., 2014; Pratt et al., 2014; Ruis et al., 2017; Stetson et al., 2012; Wegner et al., 2015). This effect is dependent on the cover crop having sufficient germination success and growth. Cover crops with longer growing periods, such as those planted after corn silage (Moore et al., 2014) or terminated at later dates (Ruis et al., 2017), may increase the likelihood of soil benefits accruing. During a 9-yr study in Iowa, cereal rye planted after corn silage harvest increased soil organic matter, particulate organic matter, and potentially mineralizable N by 15, 44, and 38%, respectively (Moore et al., 2014).

As described above, several interacting variables can influence stover harvest effects on soil properties, including location, crop yields, removal rates, tillage, and use of cover crops. Stover harvest guidelines must consider these site-specific factors to ensure soil resources are maintained over time. Soil samples must be taken to validate these guidelines. Soil samples can be analyzed for individual properties, as was discussed above and can also be evaluated via a multivariate approach such as the Soil Management Assessment Framework (SMAF) (Andrews et al., 2004). Data from both methods can provide information on how soil properties are changing individually and collectively.

Existing data suggest that producers may be reluctant to harvest stover beyond the proposed 40% threshold. For example, in Iowa, the estimated corn stover removal rate is 3.9 Mg ha^{-1} (Schmer et al., 2017), which, assuming a grain yield of 9 to 10 Mg ha^{-1} and a harvest index of 0.5 (Linden et al., 2000), confirms that the removal rate is ~40%. Producers surveyed in Illinois and Missouri were willing to remove corn stover at rates of 40 and 32%, respectively (Altman and Sanders, 2012). When prompted in a 2006 agricultural survey with two stover removal rates (50 or 70%), Iowa farmers expected more negative soil effects at the 70% removal rate, including increased erosion and nutrient loss (Tyndall et al., 2011). Furthermore, 48% of farmers surveyed were not interested in marketing corn stover (Tyndall et al., 2011).

Our objective was to quantify stover harvest rate, tillage practice, and cover crop effects on soil physical, chemical, and biological properties after 5 yr of continuous corn production in central Iowa. This approach fits within a soil health framework because we were interested in soil physical, chemical, and biological responses and their interactions. We hypothesized that the results could contribute to future protocols for refining regional and site-specific stover harvest guidelines for typical Iowa production systems that include different stover harvest, tillage, and cover crop strategies.

METHODS

Site History

Field plots were located at 42°1'3.3024"N, 93°45'52.128"W. Treatments were established in 2008, and represented one location in a larger bioenergy feedstock study (Karlen et al., 2014a). The soils at the site were primarily Webster silty clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) on 0 to 2% slopes and Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludolls) on 2 to 5% slopes (Supplemental Fig. S1). Site-specific estimates suggested that slopes of 1 to 2% were common across the study location.

Prior to plot establishment, the site was used for a long-term (1976–2006) tillage and crop rotation study for which the yield and soil effects were summarized by Karlen et al. (2013a, 2013b). The previous study's plot boundaries are shown in Karlen et al. (2013a). Previous tillage effects on SOC found that no-till continuous corn treatments had an average of 30 g kg^{-1} SOC whereas moldboard plow treatments had an average of 20 g kg^{-1} SOC ($P < 0.1$). Several management steps were taken to minimize carryover effects from the long-term study. Deep (0.45 m) chisel plowing was conducted diagonally to the original plot orienta-

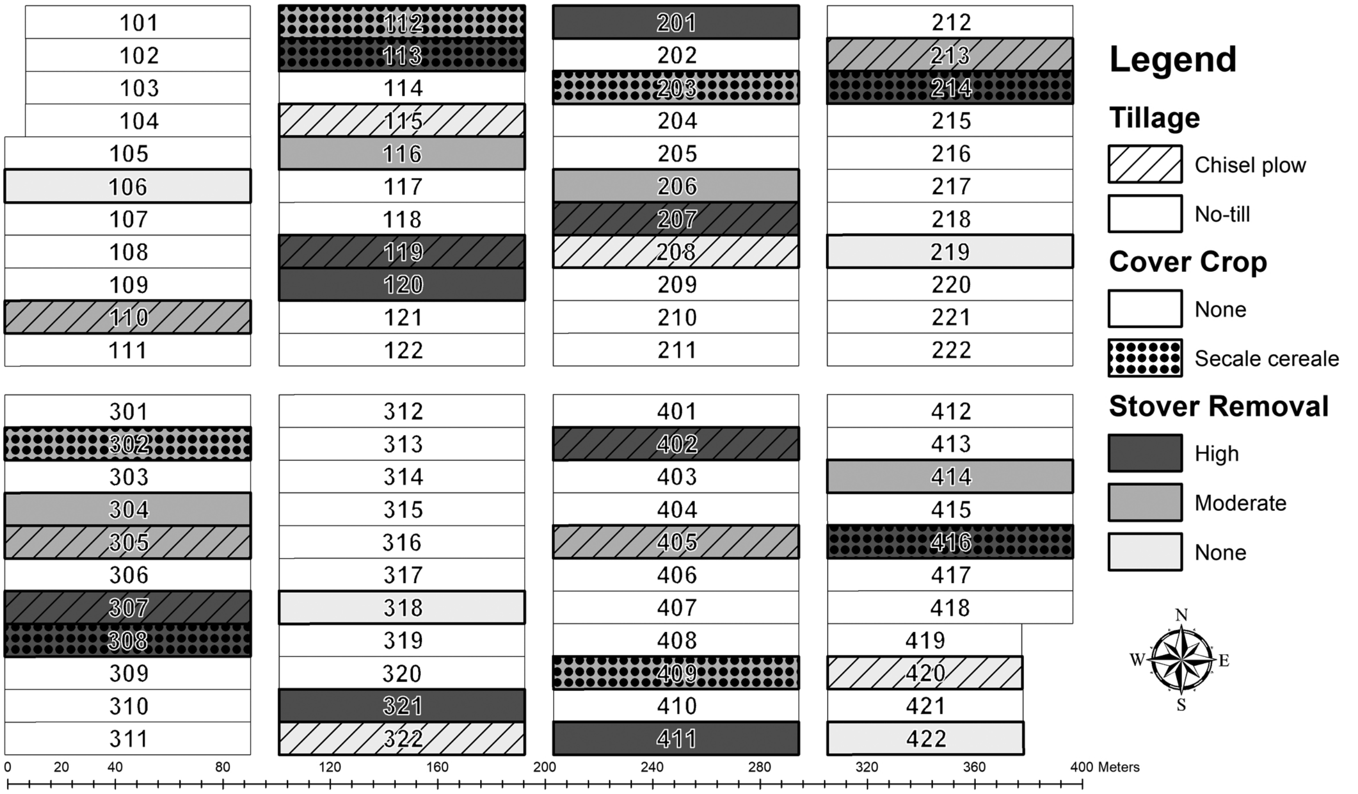

Fig. 1. Plot layout and numbers for all studied tillage, cover crop, and stover removal treatments within the larger field design. Plots 420 and 422 were 780 m^2; all other plots were 1040.5 m^2.

tion in both 2006 and 2007. During the 2007 growing season, oat (*Avena sativa* L.) was grown and harvested for both grain and straw to create a uniform pretreatment cropping effect. New plot boundaries created 88 experimental plots compared with the previous study's 40 plots.

Treatments

The data presented in this paper focus on eight continuous corn treatments combining stover harvest, tillage practice, and cover crop use (Fig. 1). Each treatment was replicated four times using 30 0.104-ha plots and two 0.078-ha plots. The smaller plots were created by grass waterways that provided surface drainage for the research site. Planting dates (Supplemental Table S2), fertilizer rates (Supplemental Table S3), and annual temperature and precipitation information (Supplemental Table S4) are included for reference. Side-dressed N fertilizer rates were increased in 2009 and 2010 to account for nutrient removal in the prior stover crop, but not in 2011 and 2012 (Supplemental Table S3), because the extra N was simply increasing NO_3–N concentrations in suction lysimeter water samples (data not presented). Estimated stover removal rates were calculated by comparing corn grain and stover yield for these eight treatments from 2008 to 2012 with the assumption that the corn grain to aboveground biomass harvest index was 0.50. Stover harvest rates were approximately 0, 35, and 60%, for none, moderate (range: 1.7–5.6 Mg DM ha^{-1}), and high (range: 3.7–8.0 Mg DM ha^{-1}) removal rates, respectively. The treatments were as follows: no-till with no stover removal (NT0), no-till with moderate stover removal (NT35), no-till with high stover removal (NT60), no-till with moderate stover removal and rye cover crop (NTR35), no-till with high stover removal and rye cover crop (NTR60), chisel plow with no stover removal (C0), chisel plow with moderate stover removal, and chisel plow with high stover removal.

Soil Sampling

Soil samples were collected following the fifth consecutive corn grain and stover harvest operation in the fall of 2012. Samples were collected across the plots, crossing into row, tracked, and untracked areas following the September harvest. Twenty-one surface samples were collected and composited for two sampling depths (0–5 and 5–15 cm) within each plot. Soil physical and biological measurements were conducted on these samples. Separate soil samples from these same two depths were collected on transects across each plot as part of annual fall soil testing. These samples were submitted to a commercial testing laboratory to measure soil nutrient data, including pH (1:1 soil/water ratio), electrical conductivity (1:1 soil/water ratio), P (Bray I extraction), and K (ammonium acetate extraction).

Surface (0–5 and 5–15 cm) physical and biological indicators were evaluated by following the methods described in Karlen et al. (2013a) and the associated cited papers. Dry bulk density was calculated by oven-drying soil subsamples at 105°C, adjusting the sampled soil mass, and dividing by the volumetric sampling increment. A modified Yoder (1936) water-stable aggregate method was used and included a 5-min test time, a sieve rotation of 125 rpm, a 1.8-cm vertical stroke length, and five sieve classes (4–8, 2–4, 1–2, 0.5–1, and 0.25–0.50 mm). Aggregate stability is reported as the mass of stable aggregates >0.25 mm divided by the initial sample mass and expressed as a percentage. Soil organic C and total N were measured with the dry combustion. Particulate organic matter C and particulate organic matter N (POM-N) were measured following Cambardella and Elliott (1992). Microbial biomass C (MBC) was measured with the fumigation and extraction procedures of Vance et al. (1987) and correction factors from Sparling and West (1988). Microbial biomass C was not measured on the cover crop treatments. Potentially mineralizable N was measured via a 28-d aerobic incubation following Drinkwater et al. (1996). Ammonium and nitrate concentrations were measured with a 2 M KCl extraction for 1 h with a 5:1 solution/soil ratio. All analyses were conducted in research laboratories except for the commercial soil testing laboratory measurements mentioned above.

Data Analysis

Soil properties were analyzed by depth (0–5 cm and 5–15 cm) with four replications for each increment. Individual soil properties were evaluated with mixed-effects ANOVA models in R (R Core Team, 2016) with field and replicate as random effects and tillage and residue removal as fixed effects. The interaction term for tillage × stover removal was included. This method compared soil effects for all treatments except for those with cover crops. Separately, cover crop effects were tested by conducting the same type of analysis using only no-till treatments with moderate or high stover removal rates in the comparison. Fixed effects for cover crop and stover removal (moderate or high only) were evaluated in this second series of analyses. In the results and discussion for this second set of analyses, only cover crop effects are discussed because this was the primary effect of interest. To assist in presentation and discussion, the results from NT35 and NT60 are repeated in the tables, as they were included in the statistical analysis of both datasets. All treatment effects were evaluated with $P < 0.1$. The tables report the mean value for each soil property and the text includes the mean value and SE. The CV was calculated for each soil property to show sample variability and help interpret the statistical results. The SD was divided by the mean and multiplied by 100 to express the CV as a percentage.

Given the multiple analyses conducted on the soil results, two decision criteria were used to determine which results to discuss and emphasize. Our criteria were: first, a tested effect needed to have statistical significance ($P < 0.1$); second, the results needed to show some ordering in their values that matched current soil science knowledge. For example, a trend would be considered to have occurred if SOC tended to be highest in soils with no stover removal, at an intermediate level with moderate stover removal, and lowest in the high stover removal treatments. Field data rarely follow these idealized relationships because of spatial variability, but these criteria were used to focus interpretation and highlight effects that may be useful for developing sustainable stover harvest guidelines. For statistically significant results that identified an ordered trend in soil effects, contrasts were generated with Tukey's honest significant difference in the lsmeans statement (Lenth, 2016) on a model without the error terms to estimate the effect size. These trends are discussed in the context of individual comparisons below.

In addition to the single-variable analysis described above, a complementary multivariate approach compared results across all treatments and sampling depths using the SMAF (Andrews et al., 2004). Nine of the listed soil indicators in Andrews et al. (2004) were analyzed, including physical (bulk density, aggregate stability), chemical (pH, electrical conductivity, soil test P, soil test K), and biological properties (total organic C, MBC, PMN). Scores were generated for each plot. The data for soil test P, soil test K, pH, and electrical conductivity were taken from the annual fall soil samples that were collected from the same sample depths (0–5 cm and 5–15 cm). The soil series that appeared to cover the largest area for each plot (Supplemental Fig. S1) was used in the SMAF scoring functions to select the dominant soil texture class. This texture class was applied to texture-specific response curves for each soil quality indicator.

Soil health indicators were scored separately by depth increment. Microbial biomass C was not analyzed for treatments that included a cereal rye cover crop. The SMAF analysis was conducted with and without the MBC data and both results are presented. Pairwise comparisons among the eight treatments for total SMAF index values without the MBC data included were analyzed with Tukey's honest significance difference test with a 90% confidence interval. Total SMAF index values for each sample were computed by averaging all measured individual indicator values. The total index values were averaged by tillage, residue removal, depth, and cover crop to identify if any trends occurred. Scoring functions continue to be refined and more research is needed to determine how to interpret the implications of significant differences among index values. All soil data are included in Supplemental File S1.

RESULTS AND DISCUSSION

Bulk Density, Water-Stable Aggregates, and C Measurements from 0 to 5 cm

A comparison of tillage and stover removal treatments indicated that increased tillage intensity and higher stover removal rates did not always lower soil aggregate stability and C-related soil properties (Table 1). Bulk density was not significantly different across the six treatments. For water-stable aggregates, separate tillage and residue removal effects were found. However, the higher values for the NT0 treatment may have affected both of these results. When compared by stover removal, the no stover removal (C0, NT0) group had a higher average than the other stover removal groups. When grouped by tillage, the no-till group average again benefitted from the NT0 aggregate stability value. Similar results in which the direction of response did not meet expectations were noted for SOC, mineral-associated C, POM-C, and MBC. The values of all five properties were slightly higher for chisel plow treatments at the moderate removal rate, but the trend was reversed for NT60. These results indicate that after five corn crops on these central Iowa soils, the measured properties were not consistently affected by tillage or stover removal rate.

Table 1. Tillage, stover removal, and cover crop treatment effects on average bulk density (BD), water-stable aggregates (WSA), and C and N measurements in surface (0–5 cm) soil.

									Mineral-associated		POM	
Treatment†	WSA‡	BD	NH_4–N	NO_3–N	MBC	PMN	TN	OC	N	C	N	C
	g 100 g^{-1}	g cm^{-3}		———μg g^{-1}———			—mg g^{-1}—		μg g^{-1}	mg g^{-1}	μg g^{-1}	mg g^{-1}
C0	37	1.1	5	69	327	29	2	23	1607	18	466	6
NT0	48	1.1	30	75	299	30	3	31	1882	21	619	10
C35	34	1.1	3	69	251	22	2	27	1846	21	479	6
NT35	34	1.1	27	61	216	9	2	23	1675	18	395	5
C60	36	1.0	18	75	202	-12	2	23	1805	19	290	4
NT60	41	1.1	24	68	244	26	2	27	1886	21	529	6
NTR35	44	1.2	12	44	–	54	2	23	1614	18	448	5
NTR60	45	1.0	13	68	–	60	2	29	1853	21	593	8
Tillage and stover removal comparison												
CV	17%	7%	100%	22%	24%	226%	13%	16%	12%	13%	31%	39%
$P < 0.1$§	T, R	–	T	–	–	–	T × R	T × R	–	T × R	T, R	T, R, T × R
Cover crop and stover removal comparison												
CV	16%	7%	83%	35%	–	76%	11%	15%	13%	14%	46%	43%
P < 0.1	C	–	–	–	–	C	R	R	R	R	–	–

† C0, chisel plow with no stover removal; NT0, no-till with no stover removal; C35, chisel plow with moderate stover removal; NT35, no-till with moderate stover removal; C60, chisel plow with high stover removal; NT60, no-till with high stover removal; NTR35, no-till with moderate stover removal and cover crop; NTR60, no-till with high stover removal and cover crop; MBC, microbial biomass C; PMN, potentially mineralizable N; TN, total N; OC, organic C; POM, particulate organic matter N and C.

‡ Water-stable aggregates > 250 μm.

§ $P < 0.1$ using two-way ANOVA; T, tillage; R, residue; T × R, interaction; C, cover crop.

The most prominent effect for tillage and stover removal within the 0- to 5-cm depth increment was that NT0 had a higher POM-C value than any other treatment. However, as indicated by the CVs, POM-C also had the greatest variability with much of it resulting from the NT0 values. When compared with all other treatments, NT0 plots received the lowest amount of soil disruption, and POM-C in the NT0 treatment was approximately 1.9-fold higher than in all other treatments ($P < 0.1$).

For the no-till cover crop and stover removal comparisons (Table 1), the only statistically significant cover crop difference was for water-stable aggregates. Water-stable aggregate contrasts showed 44.6 ± 4.3 g 100 g^{-1} with cereal rye and 37.7 ± 4.3 g 100 g^{-1} without ($P < 0.1$). Stover removal effects were significant for both SOC and mineral-associated C, with greater values occurring with higher amounts of removal. These results do not agree with previous findings (Supplemental Table S1) and should not be taken to suggest that stover removal increases SOC in Iowa. Stover removal rates did not include a complete removal treatment, which would have caused a larger contrast with the no stover removal treatments. Yield data from this site during these years found that corn grain yields were similar between chisel plow and no-till soils when corn stover was removed at moderate or high rates (data not shown). These similarities in yields suggest there was not a greater amount of belowground biomass occurring in NT60. However, belowground biomass was not directly measured in this study to test this hypothesis.

Nitrogen Measurements in Surface Soil (0–5 cm)

Nitrogen application was based on stover removal rates and soil test results. A static N application rate was not used across all years. No-till soils had 3.2-fold higher NH_4–N than chisel plow soils (Table 1) with the contrast analysis showing 27.1 ± 9.3 μg g^{-1} NH_4–N for no-till and 8.6 ± 9.3 μg g^{-1} NH_4–N for chisel plow ($P < 0.1$). Statistically significant effects were also noted for total N and POM-N, but trends for both soil properties indicated mixed results for tillage and stover removal treatments. This was similar to the findings observed for the C measurements (Table 1). One example is that both POM-N and total N were lowest in NT35, whereas CP35 had the highest values (Table 1). Regardless of the associated *P*-values, we could not identify any trends in these properties indicating that soil N was systematically responding to either tillage or stover removal.

For cover crop and stover removal treatments, PMN was 56.9 ± 15.2 μg g^{-1} in cover crop treatments (NTR35 and NTR60) compared with 17.5 ± 15.2 μg g^{-1} for no-till treatments without cover crops (NT35 and NT60) ($P < 0.1$) (Table 1). Total N and mineral-associated N increased at the higher stover removal rate compared with the moderate removal rate, but these two N indicators did not respond to cover crops.

Moore et al. (2014) found that PMN averaged 45 μg N g^{-1} when rye was grown following silage in a corn silage–soybean [*Glycine max* (L.) Merr.] rotation. For plots without cover crops, PMN averaged 36 μg N g^{-1} (Moore et al., 2014). The range in the NTR35, NTR60, NT35, and NT60 PMN encompassed similar PMN values. Soils in both studies were collected from central Iowa and, collectively, these values suggest likely values for PMN collected in continuous corn and corn silage–soybean rotations.

Soil Properties in Subsurface Soil (5–15 cm)

Fewer significant effects were detected in samples from the 5- to 15-cm depth (Table 2), which is in agreement with other stover removal studies (Blanco-Canqui et al., 2014; Karlen et al.,

Table 2. Tillage, stover removal, and cover crop treatment effects on average bulk density (BD), water-stable aggregates (WSA), and C and N measurements in subsurface soil (5–15 cm).

									Mineral-associated		POM	
Treatment†	WSA‡	BD	NH_4–N	NO_3–N	MBC	PMN	TN	OC	N	C	N	C
	g 100 g^{-1}	g cm^{-3}	———	——— μg g^{-1}	———	———	—mg g^{-1}—		μg g^{-1}	mg g^{-1}	μg g^{-1}	mg g^{-1}
C0	38	1.3	3	41	207	-18	2	21	1618	18	285	3
NT0	44	1.2	3	33	212	17	2	25	1888	22	273	4
C35	41	1.2	1	32	255	7	2	26	1866	22	305	4
NT35	37	1.2	7	42	169	–7	2	21	1642	18	249	2
C60	37	1.2	6	47	205	–8	2	25	1765	20	393	5
NT60	43	1.2	2	39	207	-1	2	23	1776	21	230	2
NTR35	36	1.3	2	32	–	30	2	22	1569	18	441	5
NTR60	43	1.3	1	29	–	61	2	23	1709	19	301	4
Tillage and stover removal comparison												
CV	19%	6%	83%	33%	16%	-20%	14%	18%	12%	15%	58%	69%
$P < 0.1$§	–	–	T × R	–	T, T × R	–	–	T × R	T × R	T × R	–	–
Cover crop and stover removal comparison												
CV	18%	6%	110%	37%		196%	12%	15%	11%	14%	70%	80%
$P < 0.1$	–	–	C, R	–	–	C	–	–	–	–	–	–

† C0, chisel plow with no stover removal; NT0, no-till with no stover removal; C35, chisel plow with moderate stover removal; NT35, no-till with moderate stover removal; C60, chisel plow with high stover removal; NT60, no-till with high stover removal; NTR35, no-till with moderate stover removal and cover crop; NTR60, no-till with high stover removal and cover crop; MBC, microbial biomass C; PMN, potentially mineralizable N; TN, total N; OC, organic C; POM, particulate organic matter N and C.

‡ Water-stable aggregates > 250 μm.

§ Treatment effects $P < 0.1$ using two-way ANOVA. T, tillage; R, residue; T × R, interaction; C, cover crop.

1994; Ruis et al., 2017; Villamil and Nafziger, 2015). Trends in soil effects were not found as a result of stover removal or tillage. The primary effect ($P < 0.1$) within the 5- to 15-cm depth was that no-till with cover crops (NTR35 and NTR60) had 45.5 ± 25.2 μg g^{-1} PMN compared with -3.7 ± 25.2 μg g^{-1} PMN for no-till treatments without cover crops (NT35 and NT60). Moore et al. (2014) reported PMN values for 5- to 10-cm samples that were ~25 μg g^{-1} PMN for rye grown after both corn silage and soybean and 19 μg g^{-1} PMN for rotations that did not include rye.

The 5- to 15-cm PMN value range found in this study again bracket the findings from Moore et al. (2014). However, the broader ranges in this study compared with the Moore et al. (2014) report could be caused by several factors. Moore et al. (2014) collected soil samples from untracked inter-rows in June, but in this study, we collected samples across the entire plot in the fall. Potentially mineralizable N can fluctuate over time (Bonde and Rosswall, 1987), and values showed larger variability in no-till than conventional till soils over 18 mo (Cabrera et al., 1994). The experimental design in Moore et al. (2014) included a greater sample size with 10 replicates in two adjacent fields sampled for 2 yr.

Soil Management Assessment Framework analysis

Soil quality index and SHI scores were similar among the eight treatments within each sampling depth (Table 3). Treatments with greater levels of stover removal did not have lower indicator scores. Chemical (pH, electrical conductivity, P, and K), physical (bulk density and aggregate stability), and biological (SOC, MBC, and PMN) group average SHI scores ranged from 0.74 to 0.98, from 0.59 to 1.00, and from 0.21 to 0.96, respectively. In an actively managed soil, nutrient availability is commonly addressed through annual nutrient applications and lime applications as needed that would affect the soil from 0 to 15 cm regardless of other management factors included in this study. The range in SHI scores for physical and biological properties reflects the greater variability with these measurements than those for chemical properties in agricultural soils.

Stover harvest did not cause the index values to move outside of previously found ranges. The index values from this study (Table 3) fit within existing ranges found in agricultural soils in this region (Hammac et al., 2016; Jokela et al., 2011; Karlen et al., 2014b, 2017; Stewart et al., 2015). Generally, higher index values suggest improved soil functioning. Index values from watersheds across the Midwest from 0- to 5-cm and 5- to 15-cm samples ranged from 0.78 to 0.92 and from 0.63 to 0.75, respectively (Karlen et al., 2014b). In Wisconsin, the index values ranged from 0.81 to 0.96 and from 0.73 to 0.84 at these same depths, respectively (Jokela et al., 2011). In Indiana, total index values ranged from 0.80 to 0.95 and from 0.71 to 0.78 at these same depths, respectively (Hammac et al., 2016). Results from 264 on-farm soil samples, collected from a 0- to 15-cm sample depth, found soil index values ranged from ~0.70 to 0.98 (Karlen et al., 2017). Increasing the index value for a given farm could occur by looking at which soil property or combination of properties was lowest. Index values may also change as scoring functions are refined or if additional soil properties are included in scoring functions, such as permanganate-oxidizable C (Jokela et al., 2011). Though these four studies were not focused on stover removal in continuous corn, the results offer a useful comparison with other agricultural soils. Stewart et al. (2015) included corn stover removal at a marginally productive site in Nebraska. The no-till 50% residue removal rate lowered soil quality index scores for SOC, aggregate stability, and MBC compared with no residue removal.

Table 3. Average soil health indicator (SHI) scores for the Soil Management Assessment Framework (SMAF) for the 0- to 5- and 5- to 15-cm samples by treatment, including and excluding microbial biomass C (MBC).

	SHI with MBC		SHI without MBC†	
Treatment§	0–5 cm	5–15 cm	0–5 cm	5–15 cm
C0	0.85 ± 0.02	0.66 ± 0.02	0.87 ± 0.03ab	0.71 ± 0.02b
NT0	0.85 ± 0.04	0.72 ± 0.04	0.88 ± 0.04ab	0.78 ± 0.04ab
C35	0.81 ± 0.04	0.76 ± 0.04	0.85 ± 0.04ab	0.81 ± 0.04ab
NT35	0.76 ± 0.06	0.68 ± 0.06	0.80 ± 0.05b	0.73 ± 0.06ab
C60	0.78 ± 0.04	0.70 ± 0.01	0.83 ± 0.04ab	0.74 ± 0.01ab
NT60	0.84 ± 0.03	0.72 ± 0.04	0.89 ± 0.03ab	0.77 ± 0.04ab
NTR35	–‡	–‡	0.91 ± 0.02ab	0.83 ± 0.03ab
NTR60	–‡	–‡	0.95 ± 0.00a	0.87 ± 0.03a

† Letters indicate significant differences ($P < 0.1$) within a soil sample depth column according to Tukey's honest significance difference test.

‡Not analyzed on these samples; the pairwise comparison was only run on the results for SHI without MBC.

§ C0, chisel plow with no stover removal; NT0, no-till with no stover removal; C35, chisel plow with moderate stover removal; NT35, no-till with moderate stover removal; C60, chisel plow with high stover removal; NT60, no-till with high stover removal; NTR35, no-till with moderate stover removal and cover crop; NTR60, no-till with high stover removal and cover crop.

Management Options

When soil properties were evaluated individually, the two most prominent effects were that POM-C was highest in N0 and PMN was greater in no-till treatments with moderate or high stover removal that included cover crops. Because of the experimental design, a no-till continuous corn with stover removal and a cereal rye cover crop treatment was not included. The other effects of tillage or removal rate did not suggest common groupings by tillage intensity or removal rate (i.e. none vs. high) (Table 1 and Table 2). Soil properties did not routinely cluster by increasing rates of stover removal or tillage type. The SMAF results (Table 3) suggested that higher amounts of stover removal were not reducing average indicator scores. A nonstatistically significant trend suggested that the presence of cover crops increased indicator scores; however, these results must be considered in the context of the experimental design because cover crops were also not grown in chisel plow soils.

Although these relatively short-term results did not suggest universal soil effects from increasing the stover removal rate or by tillage treatment, some measurements agreed with previous findings. The soil results for C0 and NT0 were similar to those previously measured at this site (Karlen et al., 2013a). There was no stover removal in the original long-term continuous corn study, thus making those data a useful baseline for the C0 and NT0 samples collected in 2012. Expressed as fold differences after dividing no-till measurements by chisel plow measurements, the results from the long-term study showed 1.3-, 1.2-, 1.7-, 1.4-, and 1.6-fold increases in water-stable aggregates, SOC, MBC, PMN, and POM-C, respectively, for no-till management within the 0- to 5-cm sampling depth (Karlen et al., 2013a).

Comparing NT0 and C0 means from the 0- to 5-cm 2012 sampling data (Table 1) the no-till treatments increased water-stable aggregates, SOC, MBC, PMN, and POM-C by 1.3-, 1.3-, 0.9-, 1.0-, and 1.7-fold, respectively, compared with chisel plowing. Considering the trend among means from these two treatments only, the soil results from 2012 support the observed long-term trends except for MBC and PMN. Those soil effects may take a longer time period to develop, as the soils from Karlen et al. (2013a) were in continuous corn for 26 yr and the treatments in the current study have been in place only 5 yr.

The observed effects of tillage and stover removal are similar to previous studies from Illinois (Villamil and Nafziger, 2015) and New York (Moebius-Clune et al., 2008). Villamil and Nafziger (2015) found that in Illinois, the combination of chisel plow and stover removal did not always reduce SOC. In New York, tillage had a greater effect on soil properties than stover removal after 32 yr of continuous corn (Moebius-Clune et al., 2008). This is in contrast to the studies from drier regions of the U.S., where no-till is routinely practiced and irrigation may be needed to produce crops (Supplemental Table S1). For example, SOC was reduced by 9% after 3 yr of 63% corn stover removal in no-till, irrigated continuous corn in Nebraska at 0- to 2.5-cm sampling depths (Blanco-Canqui et al., 2014). Using a 55% corn stover removal rate for 12 yr in rainfed continuous corn production in Nebraska, Jin et al. (2015) found a 40% reduction in POM-C. The POM-C results from this current study demonstrate that a reduction can occur either because of stover removal or tillage.

The site selected for this research could be a suitable location for stover removal at rates close to the existing 40% recommendation. Negative trends across all soil indicators did not occur as the stover harvest rate increased. The site was not classified as highly erodible and the slopes were less than 5% in all locations. The removal rates did not include a complete removal treatment, which would have probably caused greater surface soil effects than could be seen with the estimated 35% and 60% stover removal rates. These studied rates may provide a reasonable management approach that balances residue management with soil protection. The difficulty in detecting trends related to stover removal and tillage indicates that the inherent soil variability at the site remained greater than any new variability imposed by the tillage, stover removal, or cover crop effects. Alternatively, any variability introduced only by residue removal was not greater than the existing soil effects from tillage.

On the basis of the results from this study, some stover can be removed from central Iowa soils with fewer effects on soil properties than would be seen in other regions where sustainable stover removal rates are more limited. No-till and chisel plow soils performed similarly according to the SMAF results, suggesting that either practice could be effective as a companion practice for stover removal. However, the lower impact on soil properties does not imply that stover removal has no consequences. In this study, POM-C decreased when some stover was removed, even under no-till. Particulate organic matter C is not currently included in SMAF scoring functions. The relative importance of this effect requires continued research efforts into POM-C and its effects on soil functions.

CONCLUSIONS

The results from this current study agree with previous recommendations to maintain at least 60% aboveground biomass to protect soil resources (Wilhelm et al., 2010). After 5 yr of continuous corn with three stover removal rates (0, 35, or 60%), all soil properties were not affected negatively as corn stover removal rates increased. Two key soil health indicators that reflected treatment effects were POM-C and PMN. Soil samples (0–5 cm) under NT0 had 1.9-fold higher POM-C than other treatments. In NTR35 and NTR60 increased PMN at 0 to 5 and 5 to 15 cm. The SMAF values suggested that indicator values varied by tillage, sampling depth, and cover crop use but not by residue removal. For central Iowa soils on nearly level slopes, removing stover at approximately 35 to 60% of aboveground biomass may protect soil resources while providing animal feed or bioproduct feedstock. However, the soil results for the NT0 treatment indicated that some tradeoffs will occur, such as lower POM-C when stover is removed. These findings point to the ongoing need to further our understanding of soil processes and functions to develop best residue management practices.

Supplemental Information

Supplemental Fig. S1, map of the research site. Supplemental Table S1, stover removal effects from previous studies. Supplemental Table S2, site planting information. Supplemental Table S3, fertilizer information. Supplemental Table S4, county weather and crop yield data. Dataset File S1: Soil data provided as a .csv file.

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REFERENCES

Al-Kaisi, M.M., S.V. Archontoulis, D. Kwaw-Mensah, and F. Miguez. 2015. Tillage and crop rotation effects on corn agronomic response and economic returns at seven Iowa locations. Agron. J. 107:1411–1424. doi:10.2134/agronj14.0470

Altman, I., and D. Sanders. 2012. Producer willingness and ability to supply biomass: Evidence from the U.S. Midwest. Biomass Bioenergy 36:176–181. doi:10.1016/j.biombioe.2011.10.031

Andrews, S.S., D.L. Karlen, and C.A. Cambardella. 2004. The soil management assessment framework: A quantitative soil quality evaluation method. Soil Sci. Soc. Am. J. 68:1945–1962. doi:10.2136/sssaj2004.1945

Barber, S. 1979. Corn residue management and soil organic matter. Agron. J. 71:625–627. doi:10.2134/agronj1979.00021962007100040025x

Blanco-Canqui, H., R.B. Ferguson, V.L. Jin, M.R. Schmer, B.J. Wienhold, and J. Tatarko. 2014. Can cover crop and manure maintain soil properties after stover removal from irrigated no-till corn? Soil Sci. Soc. Am. J. 78:1368–1377. doi:10.2136/sssaj2013.12.0550

Bonde, T.A., and T. Rosswall. 1987. Seasonal variation of potentially mineralizable nitrogen in four cropping systems. Soil Sci. Soc. Am. J. 51:1508–1514. doi:10.2136/sssaj1987.03615995005100060019x

Bonner, I.J., D.J. Muth, Jr., J.B. Koch, and D.L. Karlen. 2014. Modeled impacts of cover crops and vegetative barriers on corn stover availability and soil quality. Bioenergy Res. 7:576–589. doi:10.1007/s12155-014-9423-y

Cabrera, M.L., D.E. Kissel, and M.F. Vigil. 1994. Potential nitrogen mineralization: Laboratory and field evaluation. In: J.L. Havlin and J.S. Jacobson, editors, Soil testing: Prospects for improving nutrient recommendations, SSSA Spec. Publ. 40. SSSA and ASA, Madison, WI. p. 15–30.

Cambardella, C.A., and E.T. Elliott. 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56:777–783. doi:10.2136/sssaj1992.03615995005600030017x

Drinkwater, L.E., C.A. Cambardella, J.D. Reeder, and C.W. Rice. 1996. Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. In: J.W. Doran and A.J. Jones, editors, Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI. p. 217–229.

Halvorson, A.D., and C.E. Stewart. 2015. Stover removal affects no-till irrigated corn yields, soil carbon, and nitrogen. Agron. J. 107:1504–1512. doi:10.2134/agronj15.0074

Hammac, W.A., D.E. Stott, D.L. Karlen, and C.A. Cambardella. 2016. Crop, tillage, and landscape effects on near-surface soil quality indices in Indiana. Soil Sci. Soc. Am. J. 80:1638–1652. doi:10.2136/sssaj2016.09.0282

Hammerbeck, A., S.J. Stetson, S. Osborne, T. Schumacher, and J. Pikul, Jr. 2012. Corn residue removal impact on soil aggregates in a no-till corn/soybean rotation. Soil Sci. Soc. Am. J. 76:1390–1398. doi:10.2136/sssaj2011.0421

Jin, V.L., M.R. Schmer, B.J. Wienhold, C.E. Stewart, G.E. Varvel, A.J. Sindelar, et al. 2015. Twelve years of stover removal increases soil erosion potential without impacting yield. Soil Sci. Soc. Am. J. 79:1169–1178. doi:10.2136/sssaj2015.02.0053

Johnson, J.M.F., J.M. Novak, G.E. Varvel, D.E. Stott, S.L. Osborne, D.L. Karlen, et al. 2014. Crop residue mass needed to maintained soil organic carbon levels: Can it be determined? Bioenergy Res. 7:481–490. doi:10.1007/s12155-013-9402-8

Johnson, J.M.F., J.S. Strock, J.E. Tallaksen, and M. Reese. 2016. Corn stover harvest changes in soil hydrology and soil aggregation. Soil Tillage Res. 161:106–115. doi:10.1016/j.still.2016.04.004

Jokela, W., J. Posner, J. Hedtcke, T. Balser, and H. Read. 2011. Midwest cropping system effects on soil properties and on a soil quality index. Agron. J. 103:1552–1562. doi:10.2134/agronj2010.0454

Karlen, D.L., S.J. Birrell, J.M.F. Johnson, S.L. Osborne, T.E. Schumacher, G.E. Varvel, et al. 2014a. Multilocation corn stover harvest effects on crop yields and nutrient removal. Bioenergy Res. 7:528–539. doi:10.1007/s12155-014-9419-7

Karlen, D.L., C.A. Cambardella, J.L. Kovar, and T.S. Colvin. 2013a. Soil quality response to long-term tillage and crop rotation practices. Soil Tillage Res. 133:54–64. doi:10.1016/j.still.2013.05.013

Karlen, D.L., N.J. Goeser, K.S. Veum, and M.A. Yost. 2017. On-farm soil health evaluations: Challenges and opportunities. J. Soil Water Conserv. 72(2):26A–31A. doi:10.2489/jswc.72.2.26A

Karlen, D.L., and D.R. Huggins. 2014. Crop residues. In: D.L. Karlen, editor, Cellulosic energy cropping systems. John Wiley & Sons, Ltd., Hoboken, NJ. p. 131–147.

Karlen, D.L., J.L. Kovar, C.A. Cambardella, and T.S. Colvin. 2013b. Thirty-year tillage effects on crop yield and soil fertility indicators. Soil Tillage Res. 130:24–41. doi:10.1016/j.still.2013.02.003

Karlen, D.L., D.E. Stott, C.A. Cambardella, R.J. Kremer, K.W. King, and G.W. McCarty. 2014b. Surface soil quality in five midwestern cropland Conservation Effects Assessment Project watersheds. J. Soil Water Conserv. 69(5):393–401. doi:10.2489/jswc.69.5.393

Karlen, D.L., N.C. Wollenhaupt, D.C. Erbach, E.C. Berry, J.B. Swan, N.S. Eash, et al. 1994. Crop residue effects on soil quality following 10-years of no-till corn. Soil Tillage Res. 31:149–167. doi:10.1016/0167-1987(94)90077-9

Lenth, R.V. 2016. Least-squares means: The R package lsmeans. J. Stat. Softw. 69(1):1–33. doi:10.18637/jss.v069.i01

Linden, D.R., C.E. Clapp, and R.H. Dowdy. 2000. Long-term corn grain and stover yields as a function of tillage and residue removal in east central Minnesota. Soil Tillage Res. 56:167–174. doi:10.1016/S0167-1987(00)00139-2

Moebius-Clune, B.N., H.M. van Es, O.J. Idowu, R.R. Schindelbeck, D.J. Moebius-Clune, D.W. Wolfe, et al. 2008. Long-term effects of harvesting maize stover and tillage on soil quality. Soil Sci. Soc. Am. J. 72:960–969. doi:10.2136/sssaj2007.0248

Moore, E.B., M.H. Wiedenhoeft, T.C. Kaspar, and C.A. Cambardella. 2014. Rye cover crop effects on soil quality in no-till corn silage-soybean cropping systems. Soil Sci. Soc. Am. J. 78:968–976. doi:10.2136/sssaj2013.09.0401

Osborne, S.L., J.M.F. Johnson, V.L. Jin, A.L. Hammerbeck, G.E. Varvel, and T.E. Schumacher. 2014. The impact of corn residue removal on soil aggregates and particulate organic matter. Bioenergy Res. 7:559–567. doi:10.1007/s12155-014-9413-0

Owens, V.N., D.L. Karlen, J.A. Lacey, et al. 2016. Regional feedstock partnership report: Enabling the billion-ton vision. U.S. Department of Energy and Idaho National Laboratory. https://www.energy.gov/eere/bioenergy/downloads/regional-feedstock-partnership-report (accessed 14 May 2018).

Pratt, M.R., W.E. Tyner, D.J. Muth, Jr., and E.J. Kladivko. 2014. Synergies between cover crops and corn stover removal. Agric. Syst. 130:67–76. doi:10.1016/j.agsy.2014.06.008

R Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org/ (accessed 14 May 2018).

Ruis, S.J., H. Blanco-Canqui, P.J. Jasa, R.B. Ferguson, and G. Slater. 2017. Can cover crop use allow increased levels of corn residue removal for biofuel in irrigated and rainfed systems? Bioenergy Res. 10:992–1004. doi:10.1007/s12155-017-9858-z

Schmer, M.R., R.M. Brown, V.L. Jin, R.B. Mitchell, and D.D. Redfearn. 2017. Corn residue use by livestock in the United States. Agric. Environ. Lett. 2:160043. doi:10.2134/ael2016.10.0043

Sindelar, A.J., J.A. Coulter, J.A. Lamb, and J.A. Vetsch. 2013. Agronomic responses of continuous corn to stover, tillage, and nitrogen management. Agron. J. 105:1498–1506. doi:10.2134/agronj2013.0181

Smith, J.A., C.D. Yonts, M.D. Rath, and J.E. Bailie. 1990. Mass of crop residue and its relationship with soil cover for a corn, dry bean, and sugarbeet rotation. Trans. ASAE 33(5):1503–1508. doi:10.13031/2013.31501

Sparling, G.P., and A.W. West. 1988. A direct extraction method to estimate soil microbial C: Calibration in situ using microbial respiration and 14C labeled cells. Soil Biol. Biochem. 20:337–343. doi:10.1016/0038-0717(88)90014-4

Stetson, S.J., S.L. Osborne, T.E. Schumacher, A. Eynard, G. Chilom, J. Rice, et al. 2012. Corn residue removal impact on topsoil organic carbon in a corn-soybean rotation. Soil Sci. Soc. Am. J. 76:1399–1406. doi:10.2136/sssaj2011.0420

Stewart, C.E., R.F. Follett, E.G. Pruessner, G.E. Varvel, K.P. Vogel, and R.B. Mitchell. 2015. Nitrogen and harvest effects on soil properties under rainfed switchgrass and no-till corn over 9 years: Implications for soil quality. Glob. Change Biol. Bioenergy 7:288–301.

Swan, J.B., E.C. Schneider, J.F. Moncrief, W.H. Paulson, and A.E. Peterson. 1987. Estimating corn growth, yield, and grain moisture from air growing degree days and residue cover. Agron. J. 79:53–60. doi:10.2134/agronj1987.00021962007900010012x

Tyndall, J.C., E.J. Berg, and J.P. Colletti. 2011. Corn stover as a biofuel feedstock in Iowa's bio-economy: An Iowa farmer survey. Biomass Bioenergy 35:1485–1495. doi:10.1016/j.biombioe.2010.08.049

Vance, E.C., P.C. Brookes, and D.S. Jenkinson. 1987. An extraction method for measuring microbial biomass C. Soil Biol. Biochem. 19:703–707. doi:10.1016/0038-0717(87)90052-6

Villamil, M.B., and E.D. Nafziger. 2015. Corn residue, tillage, and nitrogen rate effects on soil carbon and nutrient stocks in Illinois. Geoderma 253-254:61–66. doi:10.1016/j.geoderma.2015.04.002

Wegner, B.R., S. Kumar, S.L. Osborne, T.E. Schumacher, I.E. Vahyala, and A. Eynard. 2015. Soil response to corn residue removal and cover crops in eastern South Dakota. Soil Sci. Soc. Am. J. 79:1179–1187. doi:10.2136/sssaj2014.10.0399

Wilhelm, W.W., J.R. Hess, D.L. Karlen, J.M.F. Johnson, D.J. Muth, Jr., J.M. Baker, et al. 2010. Balancing limiting factors and economic drivers for sustainable midwestern US agricultural residue feedstock supplies. Ind. Biotechnol. (New Rochelle N.Y.) 6:271–287. doi:10.1089/ind.2010.6.271

Wilhelm, W.W., J.M.F. Johnson, D.L. Karlen, and D.T. Lightle. 2007. Corn stover to sustain soil organic carbon further constrains biomass supply. Agron. J. 99:1665–1667. doi:10.2134/agronj2007.0150

Yoder, R.E. 1936. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. J. Am. Soc. Agron. 28:337–351. doi:10.2134/agronj1936.00021962002800050001x