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Corn (*Zea mays* L.) stover (non-grain aboveground biomass) in the US Corn Belt is used increasingly for livestock grazing and co-feed and for cellulosic bioenergy production. Continuous stover removal, however, could alter long-term agricultural productivity by affecting soil organic C (SOC) and soil physical properties, indicators of soil fertility and erosion potential. In this study, we showed that 12 consecutive yr of 55% stover removal did not affect mean grain yields at any N fertilizer rate (4.5, 6.3, and 6.0 Mg ha^{-1} for 60, 120, and 180 kg N ha^{-1} yr^{-1}, respectively) in a marginally productive, rainfed continuous corn system under no-till (NT). Although SOC increased in the top 30 cm of all soils since 1998 (0.54–0.79 Mg C ha^{-1} yr^{-1}), stover removal tended to limit SOC gains compared with no removal. Near-surface soils (0–5-cm depth) were more sensitive to stover removal and showed a 41% decrease in particulate organic matter stocks, smaller mean weight diameter of dry soil aggregates, and lower abundance of water-stable soil aggregates compared with soils with no stover removal. Increasing N fertilizer rate mitigated losses in total water-stable aggregates in near-surface soils related to stover removal. Collectively, however, our results indicated soil structure losses in surface soils due to lower C inputs. Despite no effect on crop yields and overall SOC gains with time using NT management, annually removing stover for 12 yr resulted in a higher risk of wind and water erosion at this NT continuous corn site in the western Corn Belt.

Abbreviations: MWD, mean weight diameter; NT, no-till; POM, particulate organic matter; SOC, soil organic carbon; ΔSOC, soil organic carbon change with time.

Large supplies of corn stover associated with extensive grain production in the US Corn Belt has supported the rapid rise in demand for stover grazing, bedding, and co-feed by the livestock industry (Klopfenstein et al., 1987; Schreck et al., 2010; Wienhold et al., 2012). High biomass availability also makes corn stover a prime feedstock candidate for bioenergy production (USDOE, 2005, 2011; Graham et al., 2007; Karlen et al., 2011b). Increased stover demand, in combination with improved crop breeding and agricultural management practices, could lead to the expansion of corn production on marginally productive croplands (defined here as fields with crop yields ≤75% of the regional average; Schmer et al., 2014), which may be more sensitive to potential land degradation. Whether stover is removed for livestock or bioenergy purposes, the amount of stover left in the field is a critical sustainability factor for soil fertility and grain production (Wilhelm et al., 2007). Some stover removal, especially in NT systems, can ameliorate potential yield reductions as a result of high stover biomass interfering with planting operations and stand establishment as well as potentially increasing dis-

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ease incidence (Swan et al., 1994; Verma et al., 2005). Excessive stover removal, however, can have negative impacts on productivity by increasing soil erosion and decreasing SOC (Mann et al., 2002; Jarecki and Lal, 2003; Wilhelm et al., 2007; Johnson et al., 2011; Laird and Chang, 2013; Kenney et al., 2015).

Expected rates of stover removal to sustain SOC or to control erosion range from 25 to 50% of total non-grain aboveground biomass and will depend on other agricultural practices such as tillage and N fertilizer management (Wilhelm et al., 2004, 2007; Graham et al., 2007; Blanco-Canqui and Lal, 2009; Johnson et al., 2011; Sindelar et al., 2015). Further, higher levels of stover retention are needed to maintain SOC compared with the levels needed for only erosion control (Wilhelm et al., 2004). Because NT can help build SOC and reduce soil erosion, it is often recommended as a companion conservation practice to stover removal (USDOE, 2005; Wilhelm et al., 2007; Moebius-Clune et al., 2008; Johnson et al., 2014). Off-site removal of stover decreases organic C inputs into the soil, which are key for maintaining soil organic matter (SOM). Soil organic matter supports microbial activities involved in soil C and nutrient cycling, soil aggregate formation, and the physical stabilization of aggregates by root turnover and soil microbial exudates (Tisdall and Oades, 1982; Jastrow and Miller 1997; Six et al., 2006). No-till practices have been shown to build SOM, particularly in surface soils (<30-cm depth) (Paustian et al., 1997; West and Post, 2002; Blanco-Canqui and Lal, 2008). Increased crop production and biomass inputs associated with N fertilizer use also could lead to greater SOC accrual to mitigate potential stover removal impacts (Follett et al., 2012), especially when used with NT (Malhi et al., 2006; Lemke et al., 2010). Alternatively, increased SOM decomposition stimulated by synthetic N fertilizer applications could lead to losses in SOC despite increased crop productivity, with SOC changes further exacerbated by stover removal (Khan et al., 2007).

Agricultural management practices that reduce C inputs (e.g., stover removal) and/or increase nutrient cycling (e.g., N fertilization) can increase erosion risks by changing the distribution and stability of soil aggregates. Soil aggregation is a function of soil texture and mineralogy interacting with C substrate and decomposition processes. Particulate organic matter, the microbially labile component of SOM, acts as nucleation sites for soil aggregate formation and is highly sensitive to management (Golchin et al., 1994; Gregorich et al., 1994; Six et al., 1999; Gale et al., 2000). Further, the stability of aggregates is linked to aggregate size, with larger macroaggregates generally turning over faster than smaller microaggregates (Six et al., 1999; Denef et al., 2004). The presence of plant residues on the soil surface additionally protects the soil against raindrop impact and moderates the intensity of freeze–thaw or wetting–drying cycles (Layton et al., 1993) to allow the formation of larger, more stable aggregates and subsequent accretion of SOC (Wienhold et al., 2013).

Because of their sensitivities to management, agricultural practices that affect particulate organic matter (POM) are also expected to impact soil aggregation, soil structure, and potential SOC storage (Wienhold et al., 2013; Osborne et al., 2014; Stewart et al., 2015; Sindelar et al., 2015). Particulate organic matter and soil aggregation, therefore, are often used as diagnostic indicators to assess soil responses to changes in agricultural practices (Follett et al., 2015). In addition to quantifying POM fractions, soil aggregate size distributions can be assessed by using dry sieving to isolate intact aggregates of various size classes. Wet sieving each dry aggregate size class simulates potential erosional forces and isolates a more stable aggregate form (i.e., water-stable aggregates) resistant to physical disruption (Nimmo and Perkins, 2002).

Predicting the future effects of removing corn stover on system dynamics will depend on quantifying the effect of management practices on crop productivity and soils (Adler et al., 2007; Robertson et al., 2011; Schmer et al., 2014). Further, long-term field trials are necessary to accurately quantify agricultural management effects on SOC, which can take decades to be fully expressed (West and Post, 2002), even when evaluating soil fractions sensitive to management change (Cambardella et al., 2001; Stewart et al., 2015). The objectives of this study were to evaluate crop and soil responses to 12 consecutive yr of annual stover removal and N fertilization at a marginally productive cropland site in the western Corn Belt. In addition to assessing long-term stover and grain yields, changes in selected surface soil properties were also quantified (0–30 cm; bulk density, pH, SOC, POM, and soil aggregate size and stability).

MATERIALS AND METHODS

Site Description

The study is located at the University of Nebraska Agricultural Research and Development Center near Ithaca, NE (41.2° N, 96.4° W). Soils at the site consist of three series: Yutan silty clay loam (a fine-silty, mixed, superactive, mesic Mollic Hapludalf), Tomek silt loam (a fine, smectitic, mesic Pachic Argiudoll), and Filbert silt loam (a fine, smectitic, mesic Vertic Argialboll). The soils comprise 47, 35, and 18% of the study area, respectively (Soil Survey Staff, 2014). The site is representative of marginally productive cropland and was previously cropped in sorghum [*Sorghum bicolor* (L.) Moench] and soybean [*Glycine max* (L.) Merr.] under conventional disk-tillage practices.

The experiment was established in 1998 under NT management as a split-split-plot arrangement in a randomized complete block with three replications. The main plots were crop species and included continuous corn and two cultivars of switchgrass (*Panicum virgatum* L.). Only the continuous corn system is reported in this study. Split plots for continuous corn were N fertilizer rate (60, 120, or 180 kg N ha^{-1}). Split-split plots were stover management treatments (0 and 55% removal) and were 9.2 m (12.76-cm rows) wide and 30 m long. Additional information regarding the experimental design was reported by Varvel et al. (2008) and Follett et al. (2012).

During the 1998 establishment year, a soybean cultivar with transgenic tolerance to glyphosate [potassium *N*-(phosphonomethyl)glycine] was grown. Starting in 1999, glyphosate-tolerant corn hybrids with maturities and genetic packages adapted to the region were planted and have been used continuously through the present. More recent hybrids selected for this continuous corn system also include transgenic tolerance to European corn borer (*Ostrinia nubilalis* Hübner) and corn rootworm (*Diabrotica* spp.). Nitrogen fertilizer treatments were initiated in 1999 and consisted of annual applications at 60, 120, or 180 kg N ha^{-1} (hereafter 60N, 120N, and 180N, respectively). From 1999 to 2006, N fertilizer was surface applied as NH_4NO_3 (34–0–0) using a broadcast spreader when the corn plants were between vegetative stages V4 and V6. From 2007 to the present, fertilizer has been applied as urea (46–0–0) using a 12-row applicator with injection knives to place N between rows to a depth of 10 to15 cm during the V4 to V6 growth stages.

In 2000, stover management treatments were initiated: none removed (0%, only grain harvested) and stover removed (~55%). In 2000, stover was harvested in a 1.83-m-wide swath for the full 30-m length using a field flail harvester set at a 10-cm cutting height. Since 2001, Carter flail harvesters (Carter Manufacturing Co.) with large weigh boxes and load cells were used to harvest two rows (1.52 m wide, 10-cm cutting height) for the full 30-m length to obtain plot yields for corn stover. Corn stover subsamples were collected at harvest, weighed in the field, and dried at 50°C to constant mass to calculate stover dry matter removed. Mean annual rates of stover removal from 2000 to 2011 across all N fertilizer rates were 2.7 to 3.3 Mg dry matter ha^{-1} yr^{-1} or 55 ± 2% of the total non-grain aboveground biomass production. Concomitant rates of stover returned to the soil surface in the no-removal treatment were 5.2 ± 0.4, 6.0 ± 0.3, and 6.1 ± 0.1 Mg ha^{-1} for the 60N, 120N, and 180N treatments, respectively. In the stover-removed treatments, 2.2 ± 0.3, 2.9 ± 0.2, and 2.7 ± 0.2 Mg ha^{-1} of stover was returned to the soil surface for the 60N, 120N, and 180N treatments, respectively. Growing conditions for 2000 to 2011 are represented using the Palmer drought severity index (National Climate Data Center, 2015) (Fig. 1).

Biomass Sampling

Total aboveground dry matter production (stover + grain) was measured annually by hand harvesting a 4.4-m-long section of a non-border, non-grain-harvest row from each plot after physiological maturity (September or early October). Ears were removed, dried, and weighed. Stalks were cut at ground level, chopped, and weighed, and a subsample was dried at 60°C to constant mass. After the dried ears were shelled, the cob mass was added to the dried stalk mass to obtain the total stover production. Corn grain yields were determined with a plot combine equipped with a weighing unit that harvested the center three rows of each plot. In plots with no stover removal, all stover was left intact following grain harvest. In stover-removed plots, stover was removed using a field flail harvester. Harvest indices are reported as the fraction of grain production to total aboveground biomass production (e.g., grain plus stover).

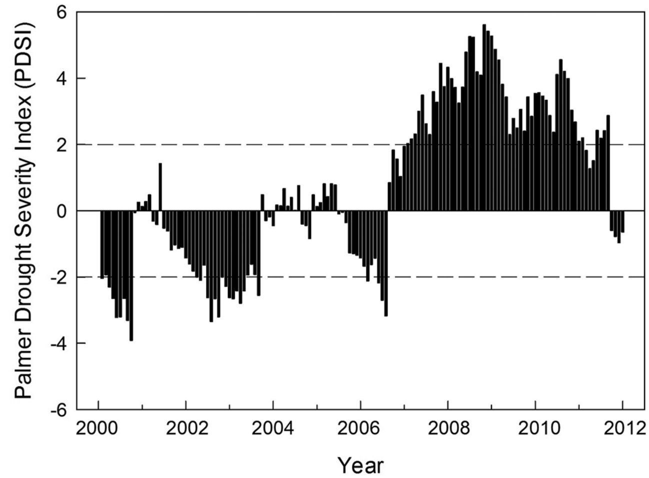

Fig. 1. Drought severity represented by the Palmer drought severity index (PDSI) for east-central Nebraska, January 2000 to December 2011. Increasing drought severity is indicated by values of −2.0 and below, and increasingly wet conditions are indicated by values ≥2.0. Values between the dashed lines represent near-normal moisture conditions.

Soil Sampling and Analyses

Baseline soil samples were collected in July 1998 from the center of each N fertilizer subplot using a flat-bladed spade to undercut and remove the soil from the 0- to 5-, 5- to 10-, and 10- to 30-cm depths. A suite of soil physical and chemical analyses was conducted. A subset of baseline data including soil bulk density (D_b), pH (1:1 water), and SOC (Follett et al., 2012; Stewart et al., 2015) is presented here to evaluate soil changes with time.

In November 2011, soils were spade sampled from the center of each N fertilizer–stover management treatment in the corn plots. Separate soil cores also were collected using a hydraulic soil corer for D_b determination in each depth increment. Spade-collected soils were air dried; a subsample was passed through a 2-mm sieve and analyzed for pH and SOC. For SOC, soils were ground into a fine powder and analyzed using a continuous-flow Europa Scientific 20-20 Stable Isotope Analyzer (isotope ratio mass spectrometer) interfaced with a Europa Scientific ANCA-NT system (automated N–C analyzer) Solid/Liquid Preparation Module (Dumas combustion sample preparation system) (Europa Scientific) (Follett et al., 1997; Follett and Pruessner, 2001). All soils were checked for carbonates, which were removed where found before analyses for organic C by the addition of 0.03 mol L^{-1} H_3PO_4, after which they were dried at 55°C and ground (Follett et al. 1997). Soil stable isotope data are not presented here.

Soil organic C stocks in 1998 and 2011 were calculated using SOC concentrations, soil D_b, and soil increments for each depth; individual layer values were summed to calculate SOC stocks for the entire 0- to 30-cm soil depth. The change in SOC stocks (ΔSOC) were calculated as the difference between 1998 and 2011 for each field replicate, then averaged to calculate treatment means and standard errors. Despite small D_b changes with time (0.05–0.15 Mg m^{-3}; Stewart et al., 2015), Follett et al. (2012) found no difference in SOC stocks whether adjusted or not for equivalent soil mass due to high field variability. The soil organic C stocks reported here are within the confidence interval of values previously reported for this site after 9 yr of treatment, so unadjusted SOC stocks are presented here.

A subsample of 2-mm-sieved soils was also used to determine the POM content using the isolation and loss-on-ignition methods described by Cambardella et al. (2001). The total POM concentration was calculated as the sum of fine POM (0.053–0.5 mm) and coarse POM (0.5–2.0 mm). Total soil stocks of POM in 2011 were calculated as described above for SOC. The remaining spade-collected air-dried soils were passed through an 8-mm sieve for determination of the dry aggregate size distribution. Bulk 8-mm-sieved samples were passed through nested sieves with a 1-min agitation time using a Ro-Tap Model B shaker (SoilTest Inc.). Sieve openings were 2.0, 1.0, 0.5, and 0.053 mm, resulting in dry aggregate fractions of >2.0, 1.0 to 2.0, 0.5 to 1.0, 0.053 to 0.5, and <0.053 mm. Individual aggregate size fractions were analyzed as grams per kilogram, and the overall size distribution was expressed as the mean weight diameter (MWD) (Kemper and Rosenau, 1986; Wienhold et al., 2013).

Water-stable aggregates were determined on subsamples from the three largest dry aggregate fractions (>2.0, 1.0–2.0, and 0.5–1.0 mm). Air-dried aggregates were saturated with deionized water by capillary wetting, then placed on 2.0, 1.0, and 0.5-mm sieves, respectively. Soils were agitated for 5 min on a wet-sieving apparatus (Five Star Scientific). The fraction of water-stable dry aggregates was determined as the percentage of soil mass retained on the sieves, adjusted for sand content (Kemper and Rosenau, 1986). The abundance of water-stable aggregates (g kg^{-1} soil) in each size class was calculated as the abundance of dry aggregates in the whole soil multiplied by the fraction of water-stable aggregates. Total water-stable aggregate abundance was calculated as the sum of the three aggregate size classes.

Statistical Analyses

A generalized linear mixed model was used to analyze stover and grain yields, soil data for each depth increment, and soil data for the cumulative 30-cm surface depth using the GLIMMIX procedure of SAS (SAS Institute, 2006; Gbur et al., 2012). For biomass yields (grain, stover, and total aboveground), D_b, pH, and SOC measurements, N fertilizer rate and stover management were considered fixed effects, block was a random effect, and year was a random effect and repeated measure. For ΔSOC, POM, MWD, and water-stable aggregates, N fertilizer rate and stover management were considered fixed effects and block was a random effect. Data were natural logarithm transformed for normality when necessary. Comparisons for significant main treatments or interactions were assessed using the LSMEANS statement (PDIFF option). Changes in SOC stocks with time (ΔSOC) were assessed for significance from zero using P values from the LSMEANS statement. All values are presented as means and standard errors. Linear regressions between various soil properties were conducted with SigmaStat (SigmaPlot 12.0, Jandel Scientific). Because high field variability decreases the statistical power to detect treatment effects, the probability of Type I errors was countered against the increasing probability of Type II errors (i.e., accepting the null hypothesis when it is false or failing to declare a real difference as significant) by considering effects significant at $P \leq 0.10$ (Zar, 1996).

RESULTS

Stover and Grain Production

From 2000 to 2011, total aboveground dry matter production (grain + stover) did not differ between stover management treatments but increased with N fertilizer rate ($P = 0.079$) (Fig. 2). Grain yields at 60N were less than those at 120N and 180N (4.5 ± 0.3, 6.3 ± 0.3, and 6.0 ± 0.4 Mg ha^{-1}, respectively; $P = 0.094$). Stover yields were less sensitive to N treatments but showed the same N response patterns ($P = 0.113$; 5.0 ± 0.3, 6.2 ± 0.2, and 6.0 ± 0.2 Mg ha^{-1}, respectively). Grain and stover yields did not differ between 120N and 180N. Across all stover and N treatments, mean harvest indices ranged from 0.46 to 0.50 (Fig. 2).

Soil Changes from 1998 to 2011

For all depth increments, soil D_b, pH, and SOC changed from 1998 to 2011 (Table 1). For the entire 0- to 30-cm depth across all N fertilizer treatments, soil D_b increased (from 1.35 to 1.44 Mg m^{-3}), pH decreased (from 6.6 to 5.9–6.3), and SOC stocks increased (from 49.4 to 57.8 Mg C ha^{-1}) ($P \leq 0.005$ for all response variables). Stover removal had no main or treatment interaction effects on these properties at any soil depth. A year × N fertilizer rate interaction for pH reflected the impact of acidification from synthetic N fertilizer use with time in the 0- to 5-cm ($P = 0.004$) and 10- to 30-cm ($P = 0.095$) soil depths, with the lowest soil pH in the cumulative 0- to 30-cm soil under 180N ($P \leq 0.01$). Stocks of SOC increased between 1998 and 2011, and the magnitude of increase was dependent on the N fertilizer

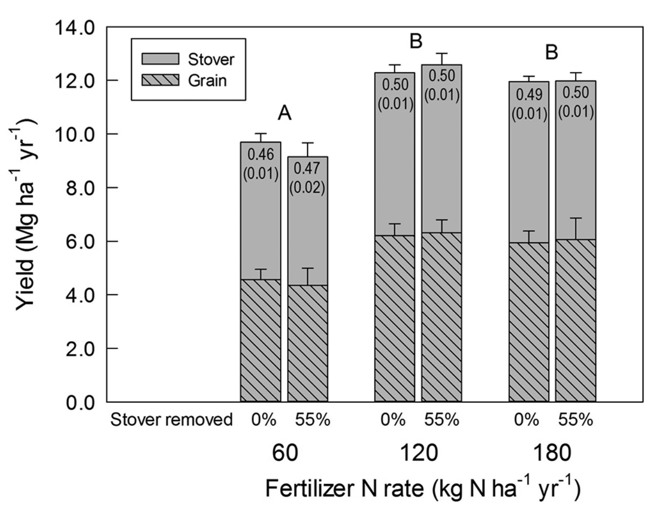

Fig. 2. Mean corn stover and grain yields (2001–2011) after initiation of stover removal treatments. Bars represent standard errors. Mean harvest index (standard error) is shown in each bar. Different uppercase letters indicate N fertilizer rate differences for total aboveground dry mass production across stover removal treatments and years.

rate interaction in the 0- to 5-cm depth. Multiple comparisons by year showed no difference in SOC stocks between N fertilizer rates in the 0- to 5-cm soil depth increment. The change in SOC (ΔSOC) from 1998 to 2011 was greater than zero for all soil increments ($P \leq 0.001$) (Table 1). The ΔSOC for the 0- to 30-cm depth did not differ among N fertilizer rates and was 6.5, 7.0, and 9.5 Mg C ha^{-1} across the 12 yr for the 60N, 120N, and 180N treatments, respectively.

Particulate Organic Matter in 2011

Total POM stocks ranged from 16.6 to 21.9 Mg ha^{-1} POM in the 0- to 30-cm soils (Fig. 3). Fine POM (0.053–0.50 mm) comprised 75 to 80% of the total POM pool, with coarse POM (0.5–2.0 mm) making up the remainder. Particulate organic matter stocks were 41% lower in soils under stover removal compared with no removal in near-surface soils (0–5 cm, $P = 0.090$) and 24% lower in cumulative surface soils (0–30 cm, $P = 0.020$). The N fertilizer rate did not affect the 2011 POM stocks at any depth. Mean concentrations (g kg^{-1}) by N treatment for POM (total, fine, and coarse) in the 0- to 5-cm soils were reported by Osborne et al. (2014).

Soil Dry Aggregate Size Distribution and Aggregate Stability in 2011

Dry aggregate size distributions were affected by stover removal. Under stover removal, the largest size class fraction (>2.0 mm) decreased at all soil depths (at 0–5 cm, from 55 to 40%, $P = 0.029$; at 5–10 cm, from 72 to 60%, $P = 0.019$; at 10–30 cm, from 72 to 68%, $P = 0.086$), with concomitant increases in all smaller size class fractions (0–5 cm, $P = 0.012$–0.033; 5–10 cm, $P = 0.012$–0.040; 10–30 cm, $P = 0.007$–0.100) except for the smallest size class (<0.053 mm). As a result, the MWD of dry aggregates decreased under stover removal compared with no removal in the 0- to 5- and 5- to 10-cm depths ($P = 0.020$ and 0.005, respectively) but not in 10- to 30-cm soils (Fig. 3). There were no main or interaction effects of N fertilizer rate on any dry aggregate size class fraction. Means by N fertilizer treatment for each aggregate size class in 0- to 5-cm soils were reported by Osborne et al. (2014).

The fraction of dry aggregates that were water stable (%) was not affected by stover removal or N fertilizer treatment. The 0.5- to 1.0-mm size class tended to be more water stable (90%) than the 1.0- to 2.0- and >2.0-mm size classes (76–78%). Water stability also decreased with soil depth for all three size classes evaluated (0–5 cm: 78, 76, and 90%; 5–10 cm: 70, 71, and 87%; 10–30 cm: 60, 64, and 84% for 0.5–1.0, 1.0–2.0, and >2.0 mm, respectively). Across all N fertilizer and stover removal treatments, the water stability of soil aggregates >2.0 mm was positively correlated with total POM in near-surface soils (0–5 cm) ($y = 1.02x + 64.77$, $r^2 = 0.366$, $P = 0.002$) (Fig. 4).

The abundance of water-stable aggregates (g kg^{-1}) for each of the three size classes and in all soil depths decreased with corn stover removal compared with no removal ($P \leq 0.05$), except for the largest size class in the 10- to 30-cm soils ($P = 0.718$). Total water-stable aggregate abundance (0.5–8.0 mm) was affected by an N fertilizer rate × stover removal interaction ($P = 0.090$) in near-surface soils (0–5 cm) only, where water-stable aggregates decreased with stover removal at 60N ($P = 0.010$), to a lesser extent at 120N ($P = 0.100$), but not at 180N ($P = 0.714$) (Fig. 5).

Table 1. Selected properties for surface soils (0–30 cm) in 1998 and 2011 under continuous no-till corn at three N fertilizer rates (60, 120, 180 kg N ha^{-1}).

Depth	Baseline† 1998	2011		
		60 kg N ha^{-1}	120 kg N ha^{-1}	180 kg N ha^{-1}
cm				
		Bulk density, Mg m^{-3}		
0–5	1.25 ± 0.08‡***	1.42 ± 0.08	1.46 ± 0.06	1.45 ± 0.08
5–10	1.38 ± 0.08***	1.65 ± 0.05	1.64 ± 0.02	1.46 ± 0.07
10–30	1.39 ± 0.05*	1.38 ± 0.03	1.43 ± 0.01	1.40 ± 0.03
0–30	1.35 ± 0.05***	1.43 ± 0.03	1.47 ± 0.01	1.42 ± 0.02
		pH (1:1 water)		
0–5	6.52 ± 0.34***	5.97 ± 0.15 a§	5.75 ± 0.20 ab	5.45 ± 0.10 b
5–10	6.50 ± 0.31***	6.13 ± 0.13	6.17 ± 0.17	5.69 ± 0.19
10–30	6.60 ± 0.23*	6.38 ± 0.12 a	6.70 ± 0.11 b	6.01 ± 0.14 c
0–30	6.56 ± 0.24***	6.27 ± 0.13 a	6.45 ± 0.11 a	5.87 ± 0.12 b
		Soil organic C, Mg C ha^{-1}		
0–5	9.3 ± 2.0***	11.5 ± 1.0	12.6 ± 0.4	12.0 ± 0.7
5–10	9.1 ± 1.8***	11.7 ± 0.8	10.9 ± 0.2	10.0 ± 1.0
10–30	30.6 ± 8.4*	37.0 ± 3.6	32.4 ± 3.7	35.2 ± 4.5
0–30	49.4 ± 11.8***	60.2 ± 5.2	55.9 ± 4.1	57.2 ± 5.9
		ΔSoil organic C, Mg C ha^{-1}¶		
0–5	–	3.3 ± 0.7	3.7 ± 0.4	5.2 ± 0.9
5–10	–	2.5 ± 0.6	1.9 ± 0.5	2.1 ± 1.0
10–30	–	1.2 ± 0.3	0.9 ± 0.7	2.2 ± 0.9
0–30	–	7.0 ± 1.2	6.5 ± 1.1	9.5 ± 2.2

* For each depth, 1998 and 2011 are significantly different at $P \leq 0.05$.

*** For each depth, 1998 and 2011 are significantly different at $P \leq 0.001$.

† Baseline values for bulk density, soil pH, and soil organic C are from Follett et al. (2012) and Stewart et al. (2015). Note that 1998 values are averaged across all N fertilizer rates because no N fertilizer treatments had been imposed at the time of site establishment.

‡ Mean ± 1 SE.

§ Means followed by different letters indicate N fertilizer rate differences in 2011 when the N × year interaction was significant ($P \leq 0.10$). If no letter is shown, there were no statistical differences among N fertilizer rates.

¶ Stock changes in soil organic C (ΔSoil organic C) between 1998 and 2011 were greater than zero in all soils at all depths ($P \leq 0.005$).

DISCUSSION

Management Effects on Crop Yield

Corn stover removal can lead to decreases in grain yield (Wilhelm et al., 1986; Power et al., 1998; Linden et al., 2000; Blanco-Canqui and Lal, 2007), with long-term impacts on soil fertility (Laird and Chang, 2013) that can persist as long as 10 yr following the cessation of stover removal (Wilhelm et al., 1986). Previous reports from this study site have shown small but signifi-

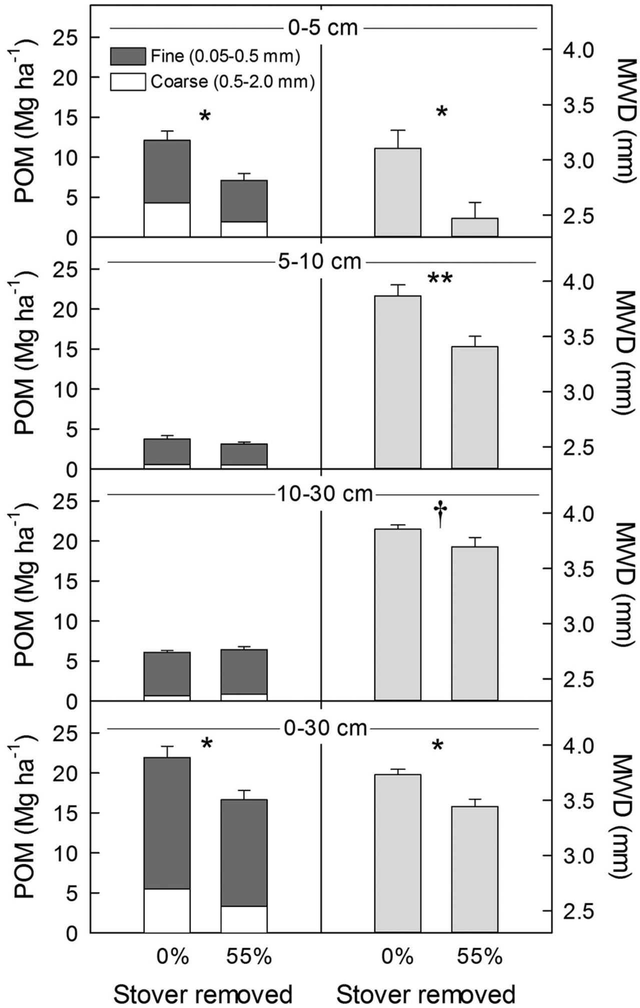

Fig. 3. Effects of 12 consecutive annual stover removal events on soil particulate organic matter (POM) stocks and aggregate mean weight diameter (MWD) in surface soils (0–30 cm) under no-till continuous corn. Bars represent standard errors. †Significant difference between stover removal treatments at $P \leq 0.10$. *Significant difference between stover removal treatments at $P \leq 0.05$. **Significant difference between stover removal treatments at $P \leq 0.01$.

cant reductions in corn grain and stover yields after the first five (2000–2005; Varvel et al., 2008) to seven stover removal events (2000–2007; Follett et al., 2012). In this study, however, we found that 12 consecutive annual events of 55% stover removal did not affect the mean stover and grain yields after initiation of removal treatments (2000–2011). Growing conditions during previous reports were predominated by drier conditions (2000–2007) compared with more recent years (2008–2011) (Fig. 1), which may have influenced stover management effects on grain and stover yields. Because stover retention can improve soil water conservation and moderate soil temperature fluctuations (Doran et al., 1984; Kenney et al., 2015), stover removal during drier years could lead to decreases in crop performance, whereas stover removal effects would be minimized during years with adequate rainfall (Wilhelm et al., 2004). Less droughty growing conditions during the last 4 yr of the study presented here (2008–2011) probably contributed to the absence of stover removal effects on corn production for the overall period of record (2000–2011).

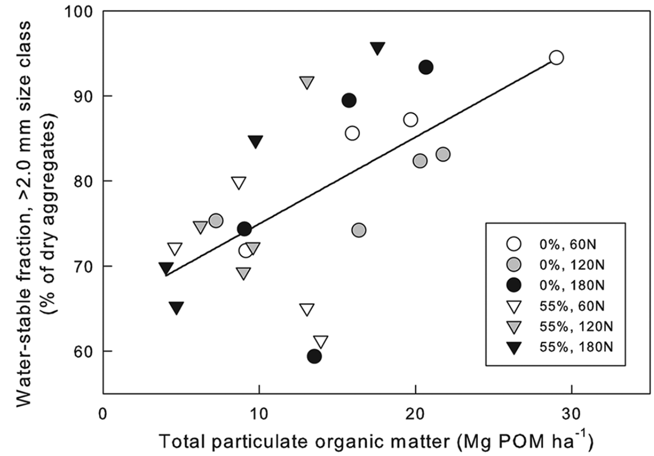

Fig. 4. Correlation between the fraction of water-stable dry aggregates in the >2.0-mm size class and total particulate organic matter (POM) in surface soils (0–5-cm depth) after 12 consecutive annual stover removal events for no-till continuous corn under three N rate treatments (60, 120, 180 kg N ha^{-1}) and two stover removal treatments (0 and 55%). Linear regression was significant: $y = 1.02x + 64.77$, $r^2 = 0.366$, $P = 0.002$.

In other regions of the US Corn Belt, stover removal also had no or variable effects on corn grain yields. Three years of stover harvest in Kansas had no short-term effects on grain yields in a continuous corn system, although stover retention tended to reduce grain yields under NT management (Kenney et al., 2015). In Iowa, 5 yr of stover harvest also had no effect on corn grain yields in a continuous corn production system (Karlen et al., 2011a), and 8 yr of stover harvest in a corn–soybean rotation system also did not affect corn grain yields in South Dakota (Hammerbeck et al., 2012). In a coordinated regional study, grain yields at 12 stover removal sites across the United States (including the current site) showed no detectable short-term differences between no stover removal and partial removal treatments (Karlen et al., 2011b). A follow-up study of 28 sites including those previous 12 sites showed that the absence of stover removal effects on 5-yr average grain yields persisted under NT practices (2008–2012) but that temporal variability in yield responses to stover removal were very high and site specific (Karlen et al., 2014). Variability in local weather, soils, study duration, and other management practices (e.g., tillage, cover crops, hybrid selection) contributed to these variable crop responses to stover management (Kenney et al., 2015; Karlen et al., 2014; Sindelar et al., 2015), with production differences occurring even at the sub-field scale (Muth et al., 2012).

Although there was no stover removal effect on crop yields in this study, yields increased between the 60N and higher N treatments (120N and 180N). This N fertilizer effect also was reported previously and has persisted with time (Follett et al., 2012). Microbial immobilization of N associated with stover decomposition was expected to decrease the overall N availability and subsequently result in crop yield decreases when no stover was removed, particularly at the lowest N fertilizer level. The absence of a N fertilizer rate × stover removal interaction effect at this marginally productive site, however, suggests that other factors (i.e., soil moisture and temperature) besides N availability are limiting yield responses to stover management in this NT system.

Management Effects on Soil Changes with Time

Soil physical, chemical, and biological responses to stover removal are likely to be most sensitive in soils nearest to the surface (Laird and Chang, 2013; Wienhold et al., 2013; Blanco-Canqui et al., 2014; Lehman et al., 2014). In this study, we found that D_b increased, soil pH decreased, and SOC increased in surface soils (0–30 cm) after 12 consecutive stover removal events compared with baseline soil values. Changes to these three soil properties with time were significant for all surface soil depths evaluated here (Table 1). A previous study also noted that stover removal resulted in greater D_b and lower soil pH at this site in 2007 but that these changes were not detected in 2004 (Stewart et al., 2015). This suggests that soil responses to changes in management practices can take several years to detect. Increases in D_b were presumably the result of a greater number of machine passes associated with stover management and has been noted in other stover removal studies (Blanco-Canqui and Lal, 2007; Karlen et al., 2011b). Lower soil pH values with increasing N fertilizer rate reflected the historical use of static rates of synthetic N fertilizer with time, specifically the use of ammoniacal fertilizer from 1999 thru 2006 as surface-broadcast NH_4NO_3, which is known to acidify soils (Barak et al., 1997).

In a previous study at this site (Stewart et al., 2015), SOC accretion rates from 1998 to 2007 were lower in the 5- to 10-cm-depth soils but higher in the 10- to 30-cm depth increment compared with the SOC changes measured from 1998 to 2011 presented here. Differences in SOC changes during these two time periods may reflect shifts in root distributions that occurred from 2007 to 2011 due to the more favorable growing conditions in recent years, as discussed above. Under drier conditions, expected root proliferation in deeper soils to support increased plant water demand (Sharp and Davies, 1985) could result in greater plant C inputs and subsequently SOC at those soil depths. Although root biomass measurements were beyond the scope of this study, these temporal differences in measured SOC stock changes demonstrate the impact that growing conditions have on biomass production and transfer of plant C to SOC.

A literature survey of corn-based systems and a recent regional survey of stover removal sites in the US Corn Belt (the multi-agency Corn Stover Regional Partnership team) estimated that 3.9 to 6.4 (5.7 ± 2.4) Mg ha^{-1} of corn stover must be returned annually to maintain SOC levels, although the large standard deviation around the mean indicated wide variability across systems (Larson et al., 1972; Johnson et al., 2010, 2014). Specifically, Johnson et al. (2014) estimated a minimum residue return rate of 2.7 Mg ha^{-1} yr^{-1} to maintain SOC in the top 30 cm of soil at this Nebraska study site. Measured mean annual stover return rates during 12 yr of management at this site approximated this estimated minimum rate in stover removal plots (2.2–2.9 Mg ha^{-1} yr^{-1} stover returned). In contrast to expectations of static SOC levels, however, SOC significantly increased

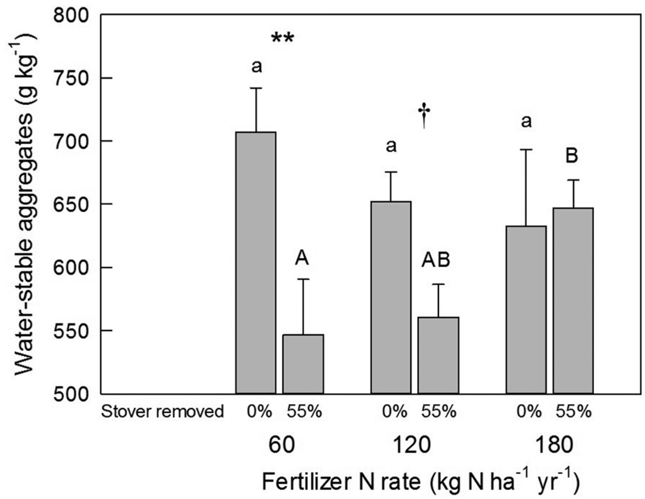

Fig. 5. Effects of 12 consecutive annual stover removal events on water-stable aggregates in the 0- to 5-cm soil depth under no-till continuous corn. Bars represent standard errors. Letters indicate N fertilizer treatment differences for 0% stover removed (lowercase) and 55% stover removed (uppercase). †Significant difference between stover removal treatments at $P \leq 0.10$. **Significant difference between stover removal treatments at $P \leq 0.01$.

with time at this site at a rate of 0.54 to 0.79 Mg C ha^{-1} yr^{-1} (Table 1). Interestingly, the stover return rate in the no-removal treatment was twofold higher (5.2–6.1 Mg ha^{-1} yr^{-1}) than when stover was removed, but the SOC accretion rate did not differ between stover removal treatments nor were they affected by the N fertilizer rate.

Compared with other study sites in the Corn Stover Regional Partnership, this Nebraska site had among the lowest baseline SOC levels when stover removal treatments were initiated (Johnson et al., 2014). Overall SOC gains in surface soils (0–30 cm) with time, regardless of stover removal or N fertilizer rate, reflected (i) the large C storage capacity in these degraded, marginally productive soils and (ii) the long-term benefits of conservation management practices at this site following conversion from conventional cropping and tillage to NT continuous corn in 1998 (Varvel et al., 2008; Follett et al., 2012; Stewart et al., 2015). Biomass inputs from continuous corn are expected to be higher than multiyear rotations alternating corn with other grain crops, resulting in greater potential SOC gains. Stratification of SOC in the absence of tillage, however, can sometimes result in relatively lower SOC levels at deeper depths in NT than tilled soils (Angers and Eriksen-Hamel, 2008; Novak et al., 2009; Dalzell et al., 2013). In addition, C inputs from deeper root growth may decrease in response to NT practices due to increases in soil bulk density and penetration resistance (Baker et al., 2007) as well as decreased rates of soil warming early in the growing season, which can also be slowed by the presence of stover (Doran et al., 1984; Layton et al., 1993; Kenney et al., 2015). While these differences at depth may not offset total SOC gains achieved by using NT, high variability in SOC stocks and in the depth distribution of SOC emphasizes the importance of evaluating the entire soil profile for SOC changes, especially in response to management decisions. Further, whether an agroecosystem acts as a C sink or source will depend on how these management decisions interact with local weather, soils, and site history across the landscape.

Management Effects on Particulate Organic Matter and Soil Aggregates

Decreased residue C inputs under stover removal significantly reduced soil stocks of POM in the entire 0- to 30-cm depth compared with no stover removal at this site, as reported previously for near-surface soils only (0–5 cm) (Osborne et al., 2014). The POM fraction was more sensitive to stover removal than the whole SOC, consistent with other studies showing that POM can be an "early warning" indicator of management impacts (Six et al., 1999; Wilhelm et al., 2007; Osborne et al., 2014; Follett et al., 2015; Sindelar et al., 2015). Because residue C acts as a nucleation site for aggregates (Six et al., 1999; Denef et al., 2004), a reduction in C inputs should directly result in a decrease in soil aggregation. Further, the physical removal of stover results in greater aggregate disruption on the soil surface, exposing organic matter previously protected within aggregates to decomposition. At this site, 12 consecutive annual stover removal events resulted in a smaller average size of dry aggregates (as MWD) due to the degradation of larger aggregates into smaller, more erodible size fractions. Reductions in MWD were pronounced for the 0- to 5- and 5- to 10-cm depths but less so in 10- to 30-cm depth. Similarly, other studies have shown disruption in aggregate formation and degradation of larger aggregate sizes in near-surface soils when crop residues are removed (Blanco-Canqui et al., 2006, 2014; Blanco-Canqui and Lal, 2009; Hammerbeck et al., 2012). In addition to the removal of C inputs, a greater number of machine passes associated with the physical removal of stover itself (e.g., chopping, raking or windrowing, baling, and bale removal) also may contribute to changes in soil physical structure, including higher soil bulk densities, greater compaction susceptibility, and changes in soil aggregate size and stability (Blanco-Canqui et al., 2006; Osborne et al., 2014; Stewart et al., 2015).

Water-stable aggregates comprised between 70 and 90% of the dry aggregates, reflecting highly structured, clayey soils. An earlier report from this site, which used an alternative method to assess wet aggregate stability, showed that the fraction of water-stable aggregates in the 0- to 5-cm depth decreased from 1998 to 2007 under stover removal (Stewart et al., 2015). Reductions in the fraction of water-stable aggregates after 3 yr of stover removal were also noted in an irrigated system in south-central Nebraska (Blanco-Canqui et al., 2014). For the 2011 soils reported here, the fraction of water-stable aggregates was generally unresponsive to stover removal, which was similar to no stability changes in soils that had different plant residues surface applied in a field decomposition study (Wienhold et al., 2013). A positive correlation between total POM and the water stability of the largest aggregate size class (>2.0 mm), however, indicated that soil structural stability increased with greater POM in these soils (Fig. 4). Other studies have noted similar relationships, suggesting that SOC losses in cultivated soils are linked to decreased soil structural stability and subsequent reductions in POM (Cambardella and Elliott, 1993; Jastrow and Miller, 1997; Wienhold et al., 2013; Follett et al., 2015).

Despite the absence of changes in the water-stable fraction, the abundance of water-stable soil aggregates (g kg^{-1}) was significantly lower in the stover removal treatment for all three aggregate size classes evaluated, largely due to the decreased relative abundances of each dry aggregate size class after stover removal. Decreases in total water-stable aggregate abundance (0.5–8.0 mm) in the near-surface (0–5 cm) soils where stover was removed, however, were offset by increasing N fertilizer rates (Fig. 5), consistent with previous observations that a higher N fertilizer rate ameliorated the degradation of larger soil aggregates and reduced the soil erodible fraction compared with lower N fertilizer rates (Osborne et al., 2014).

CONCLUSIONS

Continuous stover removal could alter long-term agricultural productivity by reducing C inputs to soil, SOC, and soil aggregation and increasing the erosion potential. In this study, we showed that 12 consecutive events removing ~55% of corn stover annually did not result in crop yield gains or losses. Further, we showed that all surface soils (0–30 cm) accrued SOC with time regardless of stover or N management practice, primarily due to the low initial SOC levels, high C storage capacity of these degraded soils, conversion to continuous corn, and the adoption of NT practices in this rainfed system. Despite measured increases in SOC stocks, >10 yr of continuous stover removal increased the erosion potential at this marginally productive site, as indicated by fewer large aggregates. This decrease was somewhat ameliorated by the higher N fertilizer rates. As a result, despite SOC accrual under NT, residue removal increased the risks of soil erosion, leading to overall reductions in soil quality with time (Stewart et al., 2015). Implementing additional conservation management practices such as cover crops or manure additions may enhance the suitability of marginally productive lands by ameliorating the increased soil erosion risks caused by stover harvesting.

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