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Perennial warm-season grasses for producing biofuel and enhancing soil properties: An alternative to corn residue removal

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Perennial warm-season grasses for producing biofuel and enhancing soil properties: An alternative to corn residue removal

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Abstract

Removal of corn (*Zea mays* L.) residues at high rates for biofuel and other off-farm uses may negatively impact soil and the environment in the long term. Biomass removal from perennial warm-season grasses (WSGs) grown in marginally-productive lands could be an alternative to corn residue removal as biofuel feedstocks while controlling water and wind erosion, sequestering carbon (C), cycling water and nutrients, and enhancing other soil ecosystem services. We compared wind and water erosion potential, soil compaction, soil hydraulic properties, soil organic C (SOC), and soil fertility between biomass removal from WSGs and corn residue removal from rainfed no-till continuous corn on a marginally productive site on a silty clay loam in eastern Nebraska after 2 and 3 yr of management. The field-scale treatments were: 1) switchgrass (*Panicum virgatum* L.), 2) big bluestem (*Andropogon gerardii* L.), and 3) low-diversity grass mixture [big bluestem, indiangrass (*Sorghastrum nutans* (L.) Nash), and sideoats grama (*Bouteloua curtipendula* (Michx.) Torr.)], and 4) 50% corn residue removal with three replications. Across years, corn residue removal increased wind erodible fraction from 41% to 86% and reduced wet aggregate stability from 1.70 to 1.15 mm compared with WSGs in the upper 7.5 cm soil depth. Corn residue removal also reduced water retention by 15% between -33 and -300 kPa potentials and plant available water by 25% in the upper 7.5 cm soil depth. However, corn residue removal did not affect final water infiltration, SOC concentration, soil fertility, and other properties. Overall, corn residue removal increases erosion potential and reduces water retention shortly after removal, suggesting that biomass removal from perennial WSGs is a desirable alternative to corn residue removal for biofuel production and maintenance of soil ecosystem services.

INTRODUCTION

Developing sustainable dedicated bioenergy cropping systems such as growing perennial WSGs is a priority to promote energy independence, enhance rural development, and improve soil ecosystem services such as erosion control, C sequestration, and water and nutrient cycling, among others. Cellulosic ethanol plants have inititated operations in the US Midwest. At present, these ethanol plants are using corn residue as the primary cellulosic feedstock source for biofuel production. Demands for corn residue likely will increase in the near future not only as feedstocks for cellulosic ethanol production but also as feed for livestock production (Sulc and Franzluebbers, 2014). Excessive removal of residue can, however, adversely impact soil and the environment in the long term (Johnson et al., 2014; Osborne et al., 2014; Jin et al., 2015). Growing dedicated bioenergy crops including switchgrass, big bluestem, and other WSGs can be an alternative to corn residue removal (Varvel et al., 2008). Dedicated bioenergy crops can supply cellulosic biomass feedstocks for bioenergy while providing essential soil ecosystem services, increasing long-term soil health.

The current questions, however, revolve around what, where, and how to grow dedicated energy crops (Johnson et al., 2010). As a result, marginally-productive lands have been identified as potential lands for the production of cellulosic biomass (Gelfand et al., 2013). In this paper, we define marginally-productive lands as croplands of low productitivity including erodible soils, sloping soils, and ocassionally flooded soils with $\leq 75\%$ crop yield of the county yield average (Mitchell et al., 2012). If succesfully established and properly managed with fertilization and organic amendments, WSGs grown in marginally-productive lands can provide cellulosic

biomass for bioenergy (Varvel et al., 2008; Follett et al., 2012; Evers et al., 2013; Stewart et al., 2015). Managing dedicated energy crops could be part of redesigned agricultural landscapes where WSGs are grown on marginally-productive lands while annual row crops are grown on prime lands to produce biomass feedstocks sustainably and enhance vegetation diversity and heterogeneity (Hartman et al., 2011; Gopalakrishnan et al., 2011; Mitchell et al., 2016).

Studies assessing soil and enviromental responses to growing energy crops in marginally-productive lands are limited (Blanco-Canqui et al., 2010). Recent studies on this topic have mostly focused on modeling the potential of marginal lands for producing biomass feedstock and ameliorating net greenhouse gas emissions (Zhang et al., 2010; Bandaru et al., 2013; Gelfand et al., 2013). Some studies have compared WSGs with continuous corn systems in their effects on SOC pools and related properties but have found some mixed results. In eastern Kansas, after 5 yr, SOC concentrations among switchgrass, big bluestem, [miscanthus (*Miscanthus* × *giganteus*)], and no-till continuous corn were not significantly different, but the WSG soils had reduced wind erodible fraction (aggregates <0.84 mm) and increased geometric mean diameter of dry aggregates compared with corn (Evers et al., 2013). On a marginally-productive site in eastern NE, switchgrass managed under 0, 60, and 120 kg N ha^{-1} fertilization levels and two harvest (harvested in August and after frost) timings had lower soil bulk density and greater aggregate stability, microbial biomass, and available P compared with no-till continuous corn after 9 yr (Stewart et al., 2015). On prime agricultural land in Ohio, Bonin et al. (2012) reported that soil bulk density and water infiltration among switchgrass, willow (*Salix spp*.), and no-till continuous corn after 7 yr did not differ.

Changes in soil properties between harvesting biomass from WSGs and harvesting residues from no-till continuous corn systems for expanded uses are not clear, and studies comparing

these systems, particularly on marginally-productive lands, are needed. Marginally productive lands are candidates for the large-scale production of WSGs. Thus, the objective of this paper was to assess wind and water erosion potential, soil compaction, soil hydraulic properties, SOC, and soil fertility under WSGs as compared with corn residue removal on marginally-productive land in eastern Nebraska. We hypothesized that despite the biomass removal of WSGs, WSGs could maintain or improve soil properties unlike corn residue removal.

Materials and Methods

Description of the experiment

This study was conducted on an ongoing bioenergy crop experiment established in 2012 on marginally-productive cropland in eastern Nebraska at the University of Nebraska-Lincoln (UNL)'s Agricultural Research and Development Center (ARDC) near Ithaca, NE. Thirty-six percent of the study site area is eroded Yutan silty clay loam (Fine-silty, mixed, superactive, mesic Mollic Hapludalfs, 2-6% slope); 35% is Tomek silt loam (Fine, smectitic, mesic Pachic Argiudolls; 0 to 2% slope); 28% is Filbert silt loam (Fine, smectitic, mesic Vertic Argialbolls; 0 to 1% slope); and <1% is Scott silt loam, frequently flooded. Average corn yield at the study site is >25% below the average rainfed production for the county and, thus is classified as marginally-productive cropland (Mitchell et al., 2012). The site prior to the experiment establishment was managed under a corn-soybean rotation for >20 years. While the study site was located on three soil series, we assumed identical soil properties in the study fields prior to the start of the experiment and assumed that all changes in measured soil properties are due to treatments. As discussed later, the particle-size distribution and management history prior to the experiment initiation did not differ among the study fields, which support our assumption.

The study treatments were: 1) 'Liberty' switchgrass, 2) big bluestem, 3) low-diversity grass mixture (big bluestem, indiangrass, and 'Butte' sideoats grama), and 4) 50% residue removal in no-till continuous corn. The three WSG treatments were arranged on a randomized complete block design in triplicate, while three plots within an adjacent corn field was used for the corn residue removal treatment. Randomization of the three corn plots was restricted to keep corn plots together to facilitate the relatively intensive management and reduce impacts of planting, spraying, harvesting, and baling equipment on adjacent WSG fields. The WSG treatments and the corn stover removal treatment were replicated three times. The size of the experimental unit for WSG was 4,000 m^2, while the size of each corn stover removal plot was 2,000 m^2. The three perennial WSG treatments also included two levels of N fertilization (56 and 112 kg N ha^{-1}) using urea. The WSG plots were the main plots while N levels were the split plots. The split plots were 38 m by 107 m in size.

Big bluestem was seeded as a 50:50 blend of 'Bonanza' and 'Goldmine' on a pure-live seed (PLS) basis. Indiangrass was seeded as a 50:50 blend of 'Scout' and 'Warrior' on a PLS basis. The WSGs were planted and established in 2012, and the N treatments were first applied in spring 2013. The equipment used for seeding was a Truax no-till grass drill (Truax Company, Minneapolis, MN). Biomass from the WSGs was harvested to an average cutting height of 10 cm above the soil surface. Corn residue from the no-till continuous corn field was removed in the fall of each year using a two-pass system consisting of a self-propelled disk mower-conditioner and round baler. The round bales were sampled for dry matter (DM) calculation and weighed to determine biomass yield.

Soil sampling and measurements

Soil properties including dry aggregate stability, wet aggregate stability, water infiltration, water retention, bulk density, Proctor bulk density, and SOC and total N concentrations were studied to assess wind and water erosion potential, changes in soil water flow and retention, soil compaction risks, and soil fertility under WSGs as compared with corn residue removal. All soil properties were measured in spring 2014 and spring 2015 except water infiltration and Proctor bulk density, which were measured in 2015.

Dry aggregate size distribution, geometric mean diameter of aggregates, and erodible fraction were assessed to determine wind erosion potential. About 2 kg of soil was collected in trays from the 0- to 5-cm depth, air-dried for 72 h, and sieved using an automated sieve shaker (Tyler Ro-Tap, Gilson Company Inc.; Nimmo and Perkins, 2002). Soil was sieved for 5 min through a stack of sieves with openings of 45, 14, 6.3, 2, 0.84, and 0.425 mm. Soil aggregates remaining in each sieve were weighed and used to compute the geometric mean diameter of aggregates and wind erodible fraction (aggregates <0.84 mm in diameter; Chepil, 1950; Nimmo and Perkins, 2002).

For the assessment of water erosion potential, wet aggregate stability was determined on bulk soil samples collected with a flat base shovel from the 0- to 7.5-cm and 7.5- to 15-cm depth. The samples were broken apart by hand, air-dried for 72 h, and passed through 8 and 4.75 mm sieves to collect aggregates with diameter ranging from 4.75 to 8 mm for the wet aggregate stability determination by the wet sieving method (Nimmo and Perkins, 2002). Fifty grams of 4.75-8 mm aggregates were placed on top of a stack of sieves with openings of 4.75, 2, 1, 0.50, and 0.25 mm. The aggregates were saturated by capillarity for 10 min and then sieved in water for another 10 min using a custom-fabricated mechanical sieving machine. Aggregates from each sieve were

transferred to beakers and oven dried at 105°C to determine the amount of water-stable aggregates and compute the geometric mean weight diameter of aggregates (Nimmo and Perkins, 2002). A fraction of the air-dry soil from each sample was crushed and passed through 2 mm sieves for the determination of sand, silt, and clay concentration by the hydrometer (Gee and Or, 2002).

For the determination of total SOC and total N concentration, a portion of the air-dry soil from the bulk samples collected for the wet aggregate stability analysis was crushed, ground in a roller mill for 24 h, and analyzed for total SOC and total N by dry combustion procedure (Nelson and Sommers, 2002). Another fraction of the air-dry soil sample was sieved through a 2-mm sieve for the analysis of pH, nitrates, available P, and exchangeable K. Soil pH was measured using 1:1 (soil:water) ratio (Thomas, 1996). Nitrate concentration was determined on soil filtrates using the cadmium reduction procedure (Gelderman and Beegle, 1998). Soil phosphorus was measured by the Mehlich-3 extraction procedure (Frank et al,. 1998). Potassium was analyzed by the ammonium acetate method (Warncke and Brown, 1998).

For the determination of bulk density and water retention characteristics, intact soil cores (7.5 cm tall by 7.5 cm diameter) were collected using a Uhland hammer-driven sampler from the 0- to 7.5- and 7.5- to 15-cm depths. The intact cores were trimmed, weighed, and saturated with tap water using a Marriote bottle for 24 h. The saturated soil cores were then weighed and transferred to the tension table for the determination of volumetric water content at 0, -1, and -3 kPa matric potentials (Dane and Hopmans, 2002). A tension table equipped with a filter paper with a bubbling pressure of -6 kPa was used for the water retention measurements at low suctions. Next, soil cores were transferred to the pressure extractors for the determination of volumetric water content sequentially at -10, -33, -100, and -300 kPa matric potentials. Water

content at -1,500 kPa matric potential was determined using high pressure extractors for air-dry soil samples passed through a 2-mm sieve. At the end of water retention measurements, soil cores were weighed and oven dried at 105°C to determine bulk density by the core method (Grossman and Reinsch, 2002). Plant available water was computed as the difference in volumetric water content between -33 kPa (field capacity) and -1,500 kPa matric potential (permanent wilting point). Soil pore size was computed using the capillary rise equation, and its distribution was estimated using the water retention data. Pores were classified as macropores (>75 µm), mesopores (30-75 µm), and micropores (<30 µm; SSSA, 2008).

To assess changes in soil compactibility (susceptibility of the soil to compaction), Proctor bulk density was determined using the standard Proctor procedure (ASTM, 2007). About 2.5 kg of bulk soil sample was collected from the 0- to 7.5-cm depth, air-dried for 72 h, and passed through a 2 mm sieve. The sieved soil was compacted at different water contents using an automatic soils compactor (ELE International; ASTM, 2007). Each water content was achieved by sequentially mixing the same soil sample with 100 ml of water. At each water content, soil was compacted in three layers in the Proctor mold using a 2.5-kg Proctor drop hammer dropping from a constant 0.30-m height. Each layer received 25 blows by the drop hammer. Proctor bulk density was computed from the mass of soil in the Proctor mold and water content.

Water infiltration was measured in the field using the double-ring metal infiltrometers (Reynolds et al., 2002). The diameter of the inner ring of the infiltrometer was 25 cm, while the diameter of the outer ring was 30 cm. Water infiltration was measured for 3 h in each plot. To account for the influence of initial soil water content on the rate of water infiltration, gravimetric water content of the soil was determined at the time of infiltration measurements.

Statistical analysis

We first analyzed the three perennial WSGs as main plots and two N fertilization levels as subplots using a split-plot analysis of variance. Results showed that N level and the WSG × N level interaction were not significant. Because neither N level, nor its interaction was significant, subsequent analyses were conducted on means across the two N fertilization levels of WSG systems. Data were then analyzed using an analysis of variance for combining separate experiments where treatments were nested in experiment. The experimental error for testing experiment effect was based on replicates only from the WSG experiment since there were no true replications from the corn residue removal experiment. Since both experiments were measured in each year, year was considered a stripped factor across all units in both experiments. This analysis resulted in the following model terms: expt rep(expt) trt(expt) rep*trt(expt) year year*expt year*rep(expt) year*trt(expt) year*rep*trt(expt). Tests were constructed assuming rep(expt) was fixed and any interaction with rep was random and Satterthwaite's correction was used to estimate the denominator degrees of freedom for the F-tests. Data analyses for volumetric water content at different soil matric potentials were conducted by soil matric potential and depth. Water infiltration analyses were conducted by time using the above model after removing all model terms that contained year. All tests including contrasts and differences in LSMEANS were evaluated at the 0.05 probability level unless otherwise stated in the paper. Pearson correlations were computed among soil properties. The SAS PROC MIXED was used to compute the ANOVA and LSMEANS and correlations were computed with PROC CORR (SAS Institute, 2015).

Ideally, the experiment effect (expt) could be used to test WSG vs corn residue removal. However, because the latter treatment was not randomized with the WSG treatments, this effect

can be confounded with other possible factors that may differ between the WSG and corn residue removal plots. To check for possible confounding factors, previous management history and soil particle-size distribution were considered. First, both WSG and corn fields were under the same management (corn-soybean rotation) prior to the experiment establishment. Second, differences in clay, silt, and sand concentration between the WSG and corn plots were not significant ($p >$ 0.10). The silt concentration for the 0- to 7.5 cm depth was 495.3±13.3 g kg^{-1} (Mean ± SD) under WSG and 524.1±19.6 g kg^{-1} under corn, whereas the clay concentration was 293.3±7.0 g kg^{-1} under WSG and 287.5±25.5 g kg^{-1} under corn. These results indicate that the soil textural class for both WSG and corn fields is silty clay loam. The similarities in management history and soil textural class between the two fields lend support to the assumption that surface soils in WSG plots were not significantly different from those in the corn plots.

Results

The 30-year average precipitation at the experimental site is 762 mm. Annual precipitation was 470 mm in 2012, 721 mm in 2013, and 875 mm in 2014. The 3-year average yield for corn at the site averaged across all treatments was 8.2 Mg ha^{-1}. The 3-year yield average on a dry matter basis was 9.6 Mg ha^{-1} for switchgrass, 7.4 Mg ha^{-1} for big bluestem, and 9.4 Mg ha^{-1} for the low diversity mixture. Detailed corn grain yield and WSG biomass yield will be reported in a separate paper as the focus of this paper was on soil properties.

Dry soil aggregate stability

Bioenergy crop treatments had significant effects on soil aggregate properties affecting wind erosion after 2 and 3 yr of management. In 2014, the difference in geometric mean diameter of dry aggregates between warm-season grasses and corn residue removal was significant only at the 0.10 probability level. There were significant treatment × year interactions where the

differences between WSGs and corn residue removal were smaller in 2014 compared with 2015 for both geometric mean diameter (Fig. 1A) and erodible fraction (Fig. 1B). Compared with WSG treatments, corn residue removal reduced geometric mean diameter by 4.8 times (from 4.03 mm to 0.83 mm) in 2014 and by 9.4 times (from 6.6 mm to 0.70 mm) in 2015. Similarly, corn residue removal increased wind erodible fraction by 1.8 times (from 46.0 mm to 81.3 mm) in 2014 and by 2.4 times (from 37.9 mm to 90.2 mm) in 2015 compared with WSG treatments (Fig. 1B).

Wet soil aggregate stability

Changes in near-surface wet soil aggregate stability are a sensitive indicator of water erosion risks. Bioenergy crop treatments affected near-surface wet soil aggregate stability in 2014 but not in 2015, indicating that effects varied from year to year. In 2014, corn residue removal reduced wet aggregate size and stability expressed as mean weight diameter of water-stable aggregates in the upper 7.5 cm soil depth compared with perennial WSG treatments but not in the 7.5- to 15-cm soil depth (Fig. 2). In 2014, corn residue removal reduced mean weight diameter of water-stable aggregates by 89% (1.46 versus 0.77 mm) compared with WSGs (Fig. 2). Wet soil aggregate stability between WSG monocultures and low diversity grass mixture did not differ, indicating that monocultures and polycultures of perennial grasses had similar effects on reducing water erosion potential. While corn residue removal did not statistically reduce mean weight diameter of water-stable aggregates in 2015, mean water-stable aggregates tended to be lower under corn residue removal than under WSGs (Fig. 2).

Bulk density, Proctor bulk density, and water infiltration

Bulk density and Proctor bulk density were measured as parameters of soil compaction in this study. Treatments had no effects on bulk density in both years (Table 1). Similarly, Proctor

maximum bulk density did not differ among the treatments. Mean Proctor maximum bulk density was 1.54 ± 0.02 Mg m^{-3} under switchgrass, 1.53 ± 0.01 Mg m^{-3} under big bluestem, 1.55 ± 0.01 Mg m^{-3} under low-diversity mixture, and 1.54 ± 0.01 Mg m^{-3} under corn with corn residue removal. Bulk density is an indicator of soil compaction status while Proctor bulk density is an indicator of the susceptibility to compaction.

Water infiltration between corn residue removal and the WSG treatments measured after 3 yr did not differ except in the first 5 min of water infiltration (Fig. 3). Plots with corn residue removed had greater water infiltration rate in the first 5 min of infiltration relative to the WSG treatments. While differences in soil water content at the time of infiltration measurements did not statistically differ among treatments, corn residue removal had lower soil water content. Mean water content was 0.22 ± 0.02 g g^{-1} (mean $\pm$ SD) for big bluestem, 0.20 ± 0.01 g g^{-1} for low-diversity grass mixture, 0.22 ± 0.01 g g^{-1} for switchgrass, and 0.20 ± 0.01 g g^{-1} for corn residue removal. Thus, the slightly lower soil water content under corn residue removal may have favored the initial water infiltration in these plots.

Water retention capacity, pore-size distribution, and plant available water

Treatments had a significant effect on water retention capacity after 2 and 3 yr, particularly at the 0- to 7.5-cm depth (Fig. 4A-D). After 2 yr, corn residue removal reduced volumetric water content at matric potentials between -10 and -1,500 kPa for the 0- to 7.5-cm depth compared with WSGs (Fig. 4A). Corn residue removal reduced water content by 14% at -10 kPa, 22% at -33 kPa, 25% at -100 kPa, and 19% at -1,500 kPa compared with the average across WSGs. After 3 yr, corn residue removal reduced volumetric water content by 10% at matric potentials between -33 and -300 kPa in the 0- to 7.5-cm depth (Fig. 4B). At the 7.5- to 15-cm depth, after 2 yr, corn residue removal reduced volumetric water content by about 14% between -10 and -300

kPa compared with switchgrass and big bluestem (Fig. 4C), but after 3 yr, differences were not significant (Fig. 4D).

Treatments also affected plant available water (Table 1). After 2 yr, corn residue removal reduced plant available water by 30% compared with WSGs in the 0-7.5 cm depth. After 3 yr, plant available water under corn residue removal did not statistically differ from WGSs, but was numerically lower compared with WSGs (Table 1). Soil aggregate stability was correlated with soil water retention capacity and plant available water under corn residue removal (Fig. 5A-B). For example, water content at -10 kPa (Fig. 5A) and -33 kPa (Fig. 5B) was moderately and positively correlated with mean weight diameter of water-stable aggregates. Similarly, plant available water was positively correlated with the mean weight diameter of water-stable aggregates (Fig. 6). The analysis of pore-size distribution showed that corn residue removal did not reduce the volume of macropores (>75 μm) or micropores (<30 μm) but increased the volume of mesopores (30-75 μm; Table 1). Compared with WSGs, corn residue removal increased the amount of mesopores by 91% after 2 yr and by 17% after 3 yr in the 0- to 7.5-cm depth.

Soil fertility properties

Treatments had no effect on soil fertility parameters such as SOC, pH, total N, nitrate-N, available P, and exchangeable K in any year (Table 2). No consistent trends in soil fertility parameters were observed among the four treatments. Soil pH tended to be lower under corn stover removal than WSGs in 2014 but not in 2015. As expected, there was a large and significant soil depth effect on all soil fertility parameters. In general, soil pH and concentrations of SOC, total N nitrate-N, available P, and exchangeable K was higher in the 0- to 7.5-cm than in

the 7.6- to 15-cm soil depth (Table 2). For example, averaged across treatments, SOC concentration was 20% higher in the 0- to 7.5-cm than in the 7.6- to 15-cm depth.

Discussion

Wind erosion potential

Results of dry soil aggregate size distribution strongly suggest that removal of corn residue at 50% from rainfed no-till continuous corn fields could increase risks of wind erosion potential unlike biomass removal from perennial WSGs (Fig. 1A-B). For example, the 700% decrease in mean dry aggregate size due to corn residue removal across both years indicates that corn residue removal can have large negative effects. Compared with WSGs, corn residue removal probably exposed soil aggregates to the atmosphere and subjected the surface aggregates to abrupt fluctuations in freeze-thaw and wet-dry cycles, which weaken aggregates and reduce their size and stability (Kenney et al., 2015). While we did not quantify WSG root biomass, WSGs had probably abundant and extensive root biomass that enmeshed the primary and secondary soil particles and stabilized soil aggregates under WSGs. While most of the switchgrass roots are concentrated in the 0 to 15 cm soil depth, some roots can extended to depths of 3 m below the soil surface (Ma et al., 200; Kibet et al., 2016). Warm-season grasses also provide uniform and dense soil cover before and after biomass harvest, protecting soil from erosion (Khanal et al., 2013). Additionally, near-surface changes in soil physical properties under corn residue removal can be due to the possible interactive effects of greater wheel traffic from cultural and corn residue removal operations in corn, less residue left on the soil surface, and less rhizomatous root structure compared with WSGs (Wilhelm et al., 2004). For example, because of its perennial nature and deep roots, switchgrass has been considered as a potential conservation grass buffer to

reduce wind velocity and wind erosion in erosion-prone environments (Bilbro et al., 1997; Fulbright et al., 2006)

Studies comparing wind erosion potential biomass removal from perennial WSGs with corn residue removal from no-till corn are not available to compare with the results of this study. In eastern Kansas, Evers et al. (2013) found that annual row crops without residue removal increased wind erodible fraction by 8 and 16% relative to dedicated bioenergy crops including switchgrass, big bluestem, and miscanthus after 4 and 5 yr of management. In our study, the increase in wind erodible fraction from the cornfield was much larger (80 to 140%) than that reported in Kansas, which is probably due to the corn residue removal in our study unlike in the previous study. Our results also indicate that dry soil aggregate stability between WSG monocultures (switchgrass and big bluestem) and low diversity grass mixture did not differ, indicating that monocultures and polycultures of perennial grasses had similar effects on controlling wind erosion potential. Similarly, Evers et al., (2013) reported that dry soil aggregate properties among switchgrass, big bluestem, and miscanthus did not differ. Our results suggest that WSGs growing in marginally productive croplands can be an alternative to corn residue removal to produce biomass feedstocks while reducing risks of wind erosion. The decrease in dry aggregate size after 2 and 3 yr of corn residue removal suggests that corn residue removal can rapidly increase risks of wind erosion following removal.

Water erosion potential

The reduced wet aggregate stability under corn residue removal suggests that removal of residue at 50% from rainfed no-till cornfields is likely to result in increased water erosion potential shortly after removal compared with biomass removal from WSGs. The smaller wet soil aggregates under corn residue removal can be more susceptible to water erosion than the

larger aggregates under WSGs. Our results agree with findings from a nearby experiment of WSGs and corn residue removal reported by Stewart et al. (2015) which found that switchgrass had greater water-stable aggregates compared with no-till continuous corn with and without residue removal after 9 yr of management. The study by Stewart et al. (2015) found that corn residue removal reduced wet aggregate stability in the 0-5, 5-10, and 10-30 cm soil depth increments after 9 yr, whereas our study found that corn residue removal reduced wet aggregate stability only in the upper 7.5 cm depth of the soil profile after 2 and 3 yr. This comparison suggests that corn residue removal can reduce wet aggregate stability to deeper depths in the long term than in the short term.

Even without residue removal, row crops often have lower aggregate stability than WSGs. In eastern Nebraska, Blanco-Canqui et al. (2014) observed that 15-yr switchgrass hedges had 70% mean weight diameter of water-stable aggregates in the 0 to 15 cm and 40% in the 15 to 60 cm soil depth relative to conventional tillage and no-till grain sorghum-soybean-corn rotation. However, in the present study, differences in mean weight diameter of water-stable aggregates between WSGs and corn residue removal were significant only in the 0 to 15 cm depth. This can be attributed to our short-term (3 yr) study compared with the 15-yr study reported by Blanco-Canqui et al. (2014). We expect that perennial WSGs such as switchgrass could improve soil aggregation at deeper depths in the long term due to the development of deep root system that can extend to deeper profile (Ma et al., 2000).

Similar to dry aggregate stability, corn residue removal likely reduced wet aggregate stability by exposing the near-surface soil aggregates to raindrop impacts and abrupt fluctuations in near-soil freeze-thaw and wet-dry cycles due to the reduced residue cover (Wienhold et al., 2013; Kenney et al, 2015). Equipment traffic, as discussed earlier, could also crush soil aggregates and

disrupt soil aggregation near the surface (Wilhelm et al., 2004). Our data on wet aggregate stability suggest that monitoring changes in soil properties with time is needed to better understand the year-to-year variability in soil properties. The findings from this study suggest that corn residue removal at 50% can rapidly reduce near-surface soil aggregate stability compared with WSGs, which can potentially increase risks of water erosion in this marginally productive land.

Soil compaction

Our results of both soil compaction parameters including bulk density and Proctor bulk density indicate that, in the short term, corn residue removal for expanded uses does not increase soil compaction risks compared with WSGs. Some previous studies comparing WSGs with row crops have found that soil bulk density under row crops can be higher than under WSGs (Bharati et al., 2002; Bonin et al., 2012; Stewart et al., 2015), but that was not the case in our study after 2 and 3 yr. Corn residue removal could increase soil compaction through two mechanisms. One, crop residue removal can result in reduced SOC concentration, which can increase the susceptibility of the soil to compaction (Wilhelm et al., 2004). Soil organic C has low bulk density and provides buffering capacity to soil, thereby reducing soil compactibility (Thomas et al., 1996; Blanco-Canqui et al., 2015). However, in our study, crop residue removal did not reduce SOC level during the study period (Table 2), which may partly explain the lack of differences in soil compaction between WSGs and crop residue removal. Two, repeated equipment traffic during corn residue collection and removal can compact soil, particularly when the soil is relatively wet during removal (Wilhelm et al., 2004). Effect of machine traffic on soil compaction could be cumulative and may increase with time after residue removal. In our study, machine traffic for removing residues during 3 yr appeared to have limited or no effects on soil

compaction. Further monitoring of traffic effect is needed to determine how the soil responds to compactive forces of field equipment as well as to possible changes in SOC concentration due to residue removal in the long term.

Water infiltration

Similar to the lack of effects on soil compaction, corn residue removal did not reduce water infiltration in the short term. Studies comparing water infiltration between WSGs and corn residue removal are not available, but several studies have compared switchgrass with row crops without residue removal and generally found lower infiltration under row crops. A study in Iowa found that switchgrass hedges had greater water infiltration rates compared with no-till corn-soybean rotations after 10 years (Rachman et al., 2004). In Ohio, Bonin et al. (2012) reported that switchgrass tended to have greater cumulative water infiltration than corn after 7 yr, but differences were not statistically significant. Recently, on a claypan soil in Missouri, switchgrass improved water infiltration and other hydraulic properties after 5 and 6 yr of management compared with corn-soybean rotations (Zaibon et al., 2017). Most previous studies reporting improved water infiltration under switchgrass were conducted after more than 5 yr of management. Thus, based on such findings, we expect that perennial WSGs in our study could increase water infiltration in the long term (> 5 yr) as WSGs develop more extensive and deeper rooting system with time (Ma et al., 2000; Rachman et al., 2004). In the short term (< 3 yr), WSGs appear to have limited potential to improve water infiltration in marginally-productive croplands.

Plant available water

While corn residue removal did not reduce water infiltration, it generally reduced the ability of the soil to retain available water compared with WSGs in the 0- to 7.5-cm depth (Table 1).

Soils under corn residue removal held more water at or near saturation (0 and -1 kPa matric potentials), but drained more rapidly than soils under WSGs at higher suctions; thus, they retained less plant available water (Table 1), which is the difference in water content between -33 kPa (field capacity) and -1,500 kPa (permanent wilting point). The reduced soil aggregate stability under corn residue removal was partly responsible for the reduced soil water retention capacity and plant available water under corn residue removal (Fig. 5A-B), indicating that water retention capacity decreased with a decrease in soil aggregate stability. Similarly, plant available water decreased with the corn residue removal-induced decrease in the proportion of water-stable aggregates (Fig. 5C).

The higher mesoporosity under corn residue removal could be related to the lower aggregate stability under this treatment. Volume of mesopores tended to increase with a decrease in wet soil aggregate stability. These results indicate that while corn residue removal did not reduce the proportion of large pores (>75 μm), it tended to increase proportion of mesopores as a result of reduced aggregate stability near the soil surface. A decrease in SOC concentration often results in reduced water retention capacity of the soil (Rawls et al., 2003), but residue removal, in this study, did not change SOC concentration after 2 and 3 yr. In addition to changes in soil aggregate stability, WSG roots possibly contributed to increased water retention capacity in our study (Ma et al., 2000). Visual observation of the soil cores from the WSG plots exhibited more abundant roots than the cores from the plots with corn residue removal, but we did not quantify the amount of roots in this study.

Row crops such as corn have been shown to have lower water retention capacity than WSGs even when residues are not removed. In Missouri, Zaibon et al. (2017) reported that soil water content under corn-soybean rotation was lower than under switchgrass at all soil water matric

potentials except at -100 and -1,500 kPa after 5 and 6 yr of management. They attributed the

increased water retention capacity under switchgrass to better soil structure and higher root

distribution. In Iowa, switchgrass hedges not only increased water retention capacity but also

increased the amount of macropores compared with the adjacent corn-soybean rotation after 10

yr (Rachman et al., 2004). While changes in other soil properties may be slow, corn residue

removal at 50%, in our study, appear to rapidly reduce near-surface plant available water

attributed to reduced soil aggregate stability relative to WSGs.

Soil carbon gains and soil fertility

The lack of significant effects of corn residue removal on SOC and other soil fertility

parameters leads to two conclusions (Table 2). One, they indicate that corn residue removal from

no-till continuous corn does not rapidly reduce SOC or fertility. Two, WSGs may not increase

SOC or soil fertility compared with no-till corn with residue removal after 2 or 3 yr on these

fine-textured soils in eastern Nebraska. Some studies have found similar results in the short term.

In eastern Kansas, after 5 yr of management, switchgrass, big bluestem, and miscanthus did not

increase SOC and total N concentration compared with no-till continuous corn (Evers et al.,

2013). Corn residue removal plots may need more years before SOC levels decreased relative to

WSG plantations or no-till continuous corn systems (Ma et al., 2000). In a nearby experiment,

Stewart et al. (2015) study found a significant increase in surface SOC in both switchgrass and

no-till continuous corn with 50% residue removal after 9 years of treatment, particularly when

additional N was supplied. As indicated earlier, changes in SOC concentration often influence

water retention in the soil; but, in this study, correlation between water retention capacity and

SOC concentration was not significant as SOC concentration did not differ among treatments.

Return of crop residues after harvest is important to maintain SOC and soil fertility levels. In this study, however, corn residue removal at 50% maintained SOC and fertility levels similar to WSGs after three years of management. We suggest that belowground biomass (roots) of corn contributed to the maintenance of SOC and fertility levels after residue removal in this fine-textured soil. Wilhelm et al. (2004) discussed that roots can contribute to SOC more than shoots or aboveground biomass. Indeed, about 75% of new SOC could be derived from roots (Gale and Cambardella, 2000), which deserves further consideration when evaluating changes in SOC after corn residue removal. Roots can decompose slower than aboveground biomass and thus maintain SOC levels, particularly in no-till soils. Surface residues not only decompose more rapidly and lose their C as CO_2 fluxes but are also more susceptible to losses (i.e., wind) than roots. It is important to note that while roots may maintain SOC levels in the short term, excessive residue removal could eventually reduce SOC levels in the long term (Wilhelm et al., 2004). In eastern Nebraska, Blanco-Canqui et al. (2014) reported that row crops without residue removal had 30% less SOC and 37% less total N than switchgrass hedges after 15 yr. Based on the above studies, we suggest that continued residue removal at high rates in our study site could reduce the SOC concentration compared with WSGs in the long term. Further monitoring of changes in SOC concentration and other soil fertility properties is needed to evaluate the long-term changes in SOC concentration in these systems.

This study comparing short-term soil response to removal of biomass from dedicated energy crops and removal of residues from no-till continuous corn on marginally productive cropland in eastern Nebraska indicates that corn residue removal at 50% can increase wind and water erosion potential compared with WSGs. Harvesting residues from no-till corn generally reduced soil dry and wet aggregate stability near the surface compared with harvesting biomass from WSGs.

Corn residue removal also tended to reduce the capacity of the soil to retain plant available water, particularly near the soil surface, which indicates that removal of residues from water-limited soils may have adverse effects on water storage. Short-term corn residue removal does not, however, reduce water infiltration and concentrations of SOC, total N, and other fertility properties relative to WSGs. In general, WSGs grown in marginally-productive croplands can be an alternative to corn residue removal to provide biomass feedstocks while reducing risks of wind and water erosion, improving water retention capacity, and improving soil health in marginally-productive lands.

Acknowledgments

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List of Figures

Fig. 1. Differences in geometric mean diameter of dry aggregates (a) and wind erodible fraction (b) among perennial warm-season grasses and residue removal from no-till continuous corn. Bars followed with different lowercase letters within the same year are significantly different. ns indicates that there were no significant differences between the two years for any energy crop treatment. The letter b with asterisk (b*), in 2014, means that the difference in geometric mean diameter of dry aggregates between warm-season grasses and corn residue removal was significant only at the 0.10 probability level.

Fig. 2. Differences in mean weight diameter of water-stable aggregates among perennial warm-season grasses and residue removal from no-till continuous corn for the 0- to 7.5-cm soil depth. Bars followed with different lowercase letters within the same year are significantly different. ns indicates that there were no significant differences between the two years for any energy crop treatment.

Fig. 3. Differences in cumulative water infiltration among perennial warm-season grasses and residue removal from no-till continuous corn. The vertical error bar at each measurement time is the LSD value to compare differences among the four treatments.

Fig. 4. Differences in soil water retention among perennial warm-season grasses and corn residue removal. Error bars are the least significant differences to compare differences among treatments.

Fig. 5. Interrelationships of mean weight diameter of water-stable aggregates with (a) volumetric water content at -10 kPa matric potential and (b) volumetric water content at -33 kPa matric potential.

Fig. 6. Interrelationships of mean weight diameter of water-stable aggregates with plant available water.

Table 1. Impact of perennial warm-season grasses and 50% residue removal from no-till continuous corn on bulk density, plant available water, and volume fraction of pores in eastern Nebraska after 2 and 3 yr of management. Means followed by the same letter within the same year and soil depth are not significantly different at the 0.05 probability level.

Bioenergy Crop Treatment	Bulk Density		Plant Available Water		Macropores		Mesopores		Micropores	
	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015
	Mg m^{-3}					m^3 m^{-3}				
					0-7.5 cm soil depth					
Switchgrass	1.264a	1.285a	0.164a	0.189a	0.036a	0.038a	0.039b	0.019b	0.215a	0.239a
Big Bluestem	1.268a	1.262a	0.156a	0.172a	0.032a	0.041a	0.052b	0.031b	0.207a	0.216a
Low Diversity Grass Mixture†	1.304a	1.295a	0.171a	0.191a	0.037a	0.033a	0.051b	0.022b	0.241a	0.243a
Corn Residue Removal	1.250a	1.179a	0.124b	0.168a	0.039a	0.023a	0.090a	0.073a	0.240a	0.263a
					7.5-15 cm soil depth					
Switchgrass	1.448a	1.440a	0.158a	0.182a	0.027b	0.026a	0.023b	0.018a	0.193a	0.216a
Big Bluestem	1.478a	1.420a	0.151a	0.179a	0.035b	0.025a	0.023b	0.012a	0.184a	0.217a
Low Diversity Grass Mixture	1.495a	1.397a	0.160a	0.195a	0.032b	0.027a	0.030ab	0.020a	0.204a	0.236a
Corn Residue Removal	1.402a	1.461a	0.159a	0.168a	0.057a	0.024a	0.038a	0.013a	0.215a	0.204a

† Low diversity grass mixture consists of big bluestem, indiangrass, and sideoats grama

Table 2. Impact of perennial warm-season grasses and 50% residue removal from no-till continuous corn on soil fertility parameters in eastern Nebraska after 2 and 3 yr of management. Means followed by the same letter within the same year and soil depth are not significantly different at the 0.05 probability level.

Bioenergy Crop Treatment	Organic C		pH		Total N		Nitrate		Available P		Exchangeable K	
	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015
	g kg^{-1}				g kg^{-1}		mg kg^{-1}					
0-7.5 cm soil depth												
Switchgrass	19.1a	18.4a	5.71a	5.53a	1.9a	1.8a	4.9a	16.3a	8a	9a	395a	496a
Big Bluestem	21.4a	18.3a	6.01a	5.92a	2.0a	1.8a	3.3a	2.0a	29a	36a	438a	570a
Low Diversity Grass Mixture	20.6a	19.1a	5.90a	5.89a	2.0a	1.8a	5.8a	7.7a	26a	20a	496a	514a
Corn Residue Removal	20.8a	20.7a	5.50a	5.85a	2.1a	2.0a	6.9a	8.6a	17a	17a	418a	506a
7.5-15 cm soil depth												
Switchgrass	14.2a	14.7a	5.36	5.49a	1.4a	1.4a	2.9a	2.6a	5a	5a	246a	254a
Big Bluestem	14.0a	14.9a	5.67a	5.57a	1.5a	1.6a	1.2a	8.6a	31a	38a	317a	340a
Low Diversity Grass Mixture	14.8a	15.5a	5.63a	5.54a	1.5a	1.5a	2.2a	1.6a	17a	16a	298a	327a
Corn Residue Removal	15.4a	16.5a	5.10a	5.30a	1.5a	1.7a	3.1a	17.2a	9a	7a	257a	278a

(a)

Corn residue removal

y = 0.028x + 0.322
r = 0.49; P = 0.05

Water Content at -10 kPa (m³ m⁻³)

(b)

Corn residue removal

y = 0.043x + 0.272
r = 0.58; P = 0.01

Water Content at -33 kPa (m³ m⁻³)

MWD (mm)

Corn residue removal

$y = 0.020x + 0.134$
$r = 0.45; P = 0.07$

Plant Available Water m³ m⁻³

MWD (mm)