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Can Cover Crop Use Allow Increased Levels of Corn Residue Removal for Biofuel in Irrigated and Rainfed Systems?

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Abstract
Corn (*Zea mays* L.) residue removal at high rates can result in negative impacts to soil ecosystem services. The use of cover crops could be a potential strategy to ameliorate any adverse effects of residue removal while allowing greater removal levels. Hence, the objective of this study was to determine changes in water erosion potential, soil organic C (SOC) and total N concentration, and crop yields under early- and late-terminated cover crop (CC) combined with five levels of corn residue removal after 3 years on rainfed and irrigated no-till continuous corn in Nebraska. Treatments were no CC, early- and late-terminated winter rye (*Secale cereale* L.) CC, and 0, 25, 50, 75, and 100% corn residue removal rates. Complete residue removal reduced mean weight diameter (MWD) of water-stable aggregates (5 cm depth) by 29% compared to no removal at the rainfed site only, suggesting increased water erosion risk at rainfed sites. Late-terminated CC significantly increased MWD of water-stable aggregates by 27 to 37% at both sites compared to no CC, but early-terminated CC had no effect. The increased MWD with late-terminated CC suggests that CC when terminated late can offset residue removal-induced risks of water erosion. Residue removal and CC did not affect SOC and total soil N concentration. Particulate organic matter increased with late-terminated CC at the irrigated site compared to no CC. Complete residue removal increased irrigated grain yield by 9% in 1 year relative to no

removal. Late-terminated CC had no effect on corn yield except in 1 year when yield was 8% lower relative to no CC due to low precipitation at corn establishment. Overall, late-terminated CC ameliorates residue removal-induced increases in water erosion potential and could allow greater levels of removal without reducing corn yields in most years, in the short term, under the conditions of this study.

Keywords: Cover crop, Residue removal, Corn yield, Aggregate stability, Soil organic C, Mean weight diameter, Winter rye, Early termination, Late termination

Introduction

Corn residue is currently the main targeted cellulosic feedstock for biofuel production because it is readily available in large quantities [16, 21, 42]. Perennial warm-season grasses are under consideration [34, 38], but large field-scale production of such feedstock sources is still limited. For example, perennial grass biomass yields in marginal lands are more variable (1 to 14 Mg ha^{-1}) [9] than corn residue yield (5 to 12 Mg ha^{-1}) [19, 40]. Furthermore, some studies suggest that corn residue removal at 50% could result in more ethanol production potential than switchgrass biomass per unit of area [20].

The concern, however, is that excessive removal of crop residues for biofuel production could increase risks of soil erosion and adversely affect soil properties, nutrient cycling, and long-term soil productivity [22, 42, 43]. As rates of residue removal increase, the adverse effects of residue removal on soil properties and subsequent soil ecosystem services could also increase [3, 6, 19, 31]. Residue removal can increase soil erosion [10, 11, 19, 20], reduce soil organic C (SOC) pools [20, 21, 36, 42], long-term soil productivity [5, 19, 20, 37, 42], and other soil services [42]. According to Wilhelm et al. [43], about 5.25 Mg ha^{-1} of corn residues are required to maintain SOC under no-tillage or conservation tillage with continuous corn in Midwestern soils including loam, silt loam, and silty clay loam, while residue cover of at least 55% is required to prevent water and wind erosion in continuous no-till corn in loamy and silty clay loam soils [10, 11].

Previous studies suggest that only 30 or 50% of corn residues can be sustainably removed for biofuel [5, 16, 42, 43]. A recent study concluded that only 1.6 Mg ha^{-1} of residue (28 million Mg across the Corn Belt) could be sustainably harvested for biofuel production [37]. These removal rates are unlikely to meet the large amount of feedstock required for biofuel production. Approximately 46 million ha at 6 Mg ha^{-1} of residue harvest are needed to meet the goals set by the US Energy Independence Security Act [21].

Improved management practices are therefore needed to allow greater amounts of corn residue removal. One such management practice can be the use of cover crop (CC) following residue removal. Pratt et al. [27] suggested that addition of CC to current corn production systems could allow for 1.8 Mg ha^{-1} more residue removal for biofuel production than fields without CC while maintaining or improving soil services. Cover crop biomass production may range from 0.5 to 6.9 Mg ha^{-1} [15]. This level of CC biomass production could ameliorate residue removal effects on soil properties because it can provide additional aboveground and belowground biomass input. In other words, the additional biomass input from CC can supplant the soil benefits lost with residue removal. This strategy could be feasible because it does not require a major change in current cropping systems. From the financial standpoint of the farmer, use of CC following residue removal could improve farm profit through improvement in soil ecosystem services [26]. Furthermore, it could contribute to the sustainable diversification of traditional cropping systems. However, information from field studies comparing effects of corn residue removal at different rates with and without CC on ecosystem services such as water erosion potential, soil fertility, soil organic C, and crop yields is limited [1, 7, 35, 41].

Corn is grown in both rainfed and irrigated lands worldwide. The level of corn residue removal for biofuel and the potential of CC to mitigate removal effects could vary with irrigation management. For example, residue removal from rainfed fields may have larger negative impacts on soils and crop yields compared with irrigated soils under the same level of residue removal due to lower residue production in rainfed systems; however, this has not been well documented. Most residue removal studies are from rainfed corn production systems [1, 26, 35, 41] and not from irrigated systems [19]. Residue production may be higher in irrigated corn than in rainfed corn. Thus, information regarding residue removal effects on soil properties is also needed in irrigated systems.

Early-terminated CC may not be as effective as late-terminated CC at offsetting negative effects of residue removal due to low biomass production. However, it is important to consider that late-terminated CC could also reduce subsequent crop yields in water-limited regions [24, 25, 30]. Further, much of the work with CC is confined to rainfed locations [1, 7, 14, 16]. Thus, experimental data from irrigated locations are limited although CC is not commonly irrigated [23, 24, 30]. Currently, there are no studies on how CC termination date combined with different rates of corn residue removal for biofuel affect soil and corn yields in both irrigated and rainfed regions. Our study is designed to address this knowledge gap. The objective of this study was to determine changes in soil properties and corn yield under early- and late-terminated CC combined with five different levels of corn residue removal on a rainfed and an irrigated no-till continuous corn system in Nebraska after 3 years of management.

Materials and Methods

Description of Study Sites and Experimental Treatments Two sites were used: (1) the University of Nebraska-Lincoln (UNL) Rogers Memorial Farm (RMF) near Lincoln, NE (40.846° N lat; 96.472° W long; 380 m asl), and (2) UNL South Central Agricultural Laboratory (SCAL) near Clay Center, NE

(40.582° N lat; 98.144° W long; 552 m asl). The soil at RMF was an Aksarben silty clay loam (fine, smectitic, mesic Typic Argiudolls) with about 3% slope, while the soil at SCAL was a Hastings silt loam (fine, smectitic, mesic Udic Argiustoll) with <1% slope. Both sites were under no-till continuous corn management. The site at RMF was planted to white corn while the site at SCAL was planted to yellow corn. The site at RMF was rainfed while the site at SCAL was sprinkler irrigated. For discussion purposes, site identification will be rainfed for RMF and irrigated for SCAL. The rainfed site was under no-till for 20 years prior to establishing the experiment, while the irrigated site was under ridge till. The 30-year mean annual temperature was 10 °C for the rainfed site and 13 °C for the irrigated site (Table 1). Mean annual precipitation across the study years was 860 mm at the rainfed site and 655 mm at the irrigated site, while the 30-year mean annual precipitation was 818 mm at the rainfed site and 688 mm at the irrigated site (Table 1). Initial SOC concentrations across treatment plots were 23.6 g kg^{-1} for the rainfed site and 22.0 g kg^{-1} for the irrigated site.

We conducted a 3-year study on a winter rye CC following corn residue removal beginning fall of 2013. The experimental design is a factorial with treatments arranged in a randomized complete block design. The treatments were five residue removal rates (0, 25, 50, 75, and 100%) and three winter rye CC treatments (no CC, early and late termination) with four replications for a total of 60 plots per site (5 removal rates × 3 CC treatments × 4 replications = 60 experimental units). The plot size was 10 m by 10 m at the rainfed site and 10 m by 7.5 m at the irrigated site. Each plot had 12 corn rows.

Table 2 shows the main field operations performed at each site. Planting of corn occurred at 80,000 plants ha^{-1} in late April each year at the rainfed site and at 84,016 plants ha^{-1} in early May at the irrigated site. Application of residue removal treatments to each plot occurred in fall in mid- to late October each year. Application of the residue removal treatments is described later. Drilling of CC occurred in fall after corn harvest. Cereal rye CC was planted at rates of 67 kg ha^{-1} at the rainfed site and 56 to 112 kg ha^{-1} at the irrigated site in late October to early November. The early-terminated CC treatment was chemically terminated in mid-April about 2 to 3 weeks before planting corn, while the late-terminated CC treatment occurred within a few days before or after planting corn in mid-May (Table 2). Application of residue removal treatments, planting of CC, and termination of CC varied annually depending on weather conditions. Cover crop seeding rate increased at the irrigated site in the last 2 years (2015 and 2016) of the experiment to achieve a better stand in the fall due to late corn harvest. Cover crops were not irrigated.

Soil Collection and Analysis

To evaluate changes in soil properties under the different rates of residue removal with and without CC, we measured wet aggregate stability and concentrations of particulate organic matter (POM), SOC, and total soil N after 3 years of management. These properties were selected because they can be more responsive to management changes than other properties in the short term [4, 11]. Soil was sampled in May 2016 at both sites after corn planting. Six soil samples of 3.1 cm diameter were collected from the shoulder of corn rows within each plot using a hand probe, separated into 0- to 5-cm and 5- to 10-cm depths, and composited by depth. Because changes in soil properties are often confined to near-surface layers in the short term, samples were not collected from deeper depths. The composite samples were gently crushed to pass an 8-mm sieve and air-dried in a forced air oven at 65 °C for 3 days.

To assess changes in water erosion potential, we determined wet aggregate stability using the wet-sieving method [18]. The air-dried soil samples were sieved to collect 4.75- to 8-mm aggregates. About 50 g of the aggregates were placed on nested sieves with openings of 4.75, 2.00, 1.00, 0.50, and 0.25 mm and re-wetted through capillary action for 10 min. Nested sieves were then mechanically sieved in water for 30 oscillations min^{-1} for 10 min. Aggregates on each sieve were washed into beakers and oven dried at 105 °C for 48 h to obtain mass of the aggregate fraction and then we computed mean weight diameter (MWD) of aggregates [17]. To characterize soil porosity, which can affect runoff or water erosion, bulk density was determined by the core method. Soil cores were collected using a hand probe for the 0- to 5- and 5- to 10- cm depths. Soil porosity was computed using bulk density data assuming particle density equal to 2.65 g cm^{-3} [4].

To assess changes in the labile fraction of soil organic matter, we determined POM concentration on a 30-g air-dried sample, dispersed with 5 g L^{-1} sodium hexametaphosphate for 24 h on a reciprocal shaker. Dispersed soil was passed through a 0.53-μm sieve and rinsed until clear. Particulate organic matter was rinsed into aluminum tins and dried at 60 °C to constant weight. Mass of POM (>0.53 μm) was recorded. Samples were heated to 450 °C in a muffle furnace for 4 h and weighed. The concentration (mg POM kg^{-1} soil) of POM was then calculated [12].

To evaluate losses or gains in soil C and fertility, we determined concentrations of SOC and total N using the dry combustion method [23]. A portion of the air-dried soil samples was ground to pass a 2 mm sieve, and about 10 g were ground to flour-like consistency with mortar and pestle. Samples were placed in scintillation vials with steel rods and ground on a roller mill for 24 h before analysis on a Flash 2000 C and N analyzer (CE Elantech, Lakewood, NJ).

Agronomic Parameters

Corn plant height was measured in 2016 on 10 plants in mid- May and at tasseling in July. The height was measured from the soil surface to the extended top leaf on the same plants from two central rows. To explain any possible differences in plant height among treatments, we monitored changes in soil temperature and moisture for CC treatments under 0, 50, and 100% removal levels in 2016 at the time of plant height measurement. Soil temperature was measured using digital thermometers at 5-cm depth, while soil moisture was measured at 12-cm depth with a time domain reflectometry probe (Spectrum Technologies, Inc., Aurora, IL).

Cover crop biomass was harvested in early April for early-terminated CC and late April or early May for late-terminated CC. Biomass was clipped at soil level from two 0.25-m^2 quadrats from each plot, air-dried at 65 °C for 2 days, and weighed. Cover crop biomass yield was then scaled up to a Mg ha^{-1} basis and assumed to have 0% moisture content at weighing. Corn grain and stalks were harvested from the center two rows of each plot for a length of 2 m to determine grain and residue yield. Corn ears were removed from the stalk without removing husks, and stalks were cut at soil level. Corn ears and stalks were weighed in the field. Three ears and three stalks were randomly selected from the harvested ears and stalks for air drying at 65 °C for 48 h before weighing. Grain was removed from the ears using a hand sheller. Both cobs and grain were dried for 24 h at 65 °C before weighing each component and calculating yield assuming 15.5% moisture content [5]. The field masses of stalks (residue) and corn ears were then corrected for moisture content and scaled up to Mg ha^{-1} using the area harvested to obtain the subsample.

To apply residue removal treatments, corn stalks were shredded at 10-cm height and residue was manually removed. To achieve the 25, 50, 75, and 100% removal rates, residue was removed from select rows and remaining residue redistributed. For example, to achieve 50% residue removal, we removed residue from six of the 12 rows and the remaining residue in the plot was redistributed among all 12 rows.

Statistical Analysis

Data were analyzed by site (rainfed and irrigated) to assess statistical differences among CC termination date and residue removal treatments using PROC MIXED in SAS software for a randomized complete block design [29]. The PROC MIXED in SAS was used to analyze data on wet aggregate stability (MWD), SOC, total soil N, particulate organic matter, CC biomass, corn growth, corn yield, stover yield, soil temperature, and soil moisture. Prior to analysis of treatment effects, normal distribution of data was studied using the Shapiro-Wilk test in PROC UNIVARIATE in SAS software by site and across all treatments. Data were normally distributed and no transformation was performed. Fixed factors were CC and corn residue removal rate, while the random factor was replication. Data were analyzed by year for CC biomass, corn yield, and stover yield. Data for MWD and particulate organic matter were analyzed by soil depth. Data for corn growth, soil temperature, and soil moisture were analyzed by date. Separation of treatment means was conducted through least significant differences at the 0.05 probability level, unless otherwise stated.

Results

Water Erosion Potential

Residue removal affected mean weight diameter of water-stable aggregates at the rainfed site (p = 0.09) and at the irrigated site (p = 0.09). Cover crop termination date affected mean weight diameter at both sites (p = 0.0097 for rainfed and p = 0.0005 for irrigated). The interaction of residue removal × CC termination date was not significant (p = 0.54 for rainfed and p = 0.14 for irrigated). Residue removal and CC termination date affected mean weight diameter only in the 0- to 5-cm depth (Figs. 1a, b and 2a, b) and not in the 5- to 10-cm depth (data not shown). At the rainfed site, residue removal effects on mean weight diameter were significant only between 100 and ≤50% removal rates. Complete removal reduced mean weight diameter (1.19 ± 0.39 mm) by up to 31% compared to ≤50% removal rates (1.56 ± 0.42 mm) (Fig. 1a). Late-terminated CC treatment increased mean weight diameter (1.70 ± 0.31 mm) by 27% relative to control (1.34 ± 0.52 mm) (Fig. 1b). At the irrigated site, residue removal at rates above 50% tended to reduce mean weight diameter but statistically, mean weight diameter was variable across residue removal rates (Fig. 2a). At this site, late-terminated CC increased mean weight diameter (1.21 ± 0.34 mm) by 37%compared to no CC (0.88 ± 0.25mm) (Fig. 2b). Early-terminated CC had no effect on wet aggregate stability at any either site. Changes in soil porosity influence water erosion. However, in this study, treatments did not affect soil porosity. Mean porosity across treatments was 0.53 cm cm^{-3} at the rainfed site and 0.52 cm cm^{-3} at the irrigated site.

Soil Organic Carbon, Total Nitrogen, and Particulate Organic Matter

Residue removal and CC termination date did not affect SOC and total N concentrations at either site (Table 3). Although not significant, mean SOC concentration tended to decrease with residue removal at the rainfed site but not at the irrigated site (Table 3). Cover crops tended to increase SOC concentration at both sites (Table 3). Residue removal did not affect POM concentration at either site; however, CC termination date affected POM concentration in the 0- to 5-cm depth at the irrigated site. Particulate organic matter was 13.5% (2 mg g^{-1}) greater with late-terminated than early-terminated CC and control at the irrigated site. Residue removal and CC termination date had no effect on POM concentration at the 5- to 10-cm depth (data not shown).

Cover Crop Biomass Yield

At the rainfed site, residue removal affected late-terminated CC biomass yield in the second (2015) and third year (2016) of the study. At the irrigated site, residue removal affected CC biomass yield only in the first year. Cover crop termination date (Table 2), as expected, affected CC biomass yield at both sites in all years (Table 4). There was an interaction of residue removal × CC at the irrigated site in the first year and at the rainfed site in the second year. At the rainfed site, complete residue removal increased CC biomass yield by 83% in the second year compared with the rest of the removal rates. At the same site, in the third year, complete residue removal increased CC biomass yield by 63% but only when compared with no removal. At the same site, late-terminated CC increased CC biomass yield by 11 times (0.03 vs. 0.32 Mg ha^{-1}) in the first year, by 1.88 times (0.80 vs. 1.50 Mg ha^{-1}) in the second year, and by 2 times (1.41 vs. 3.00 Mg ha^{-1}) in the third year compared to early-terminated CC. At the irrigated site, under early-terminated CC, complete residue removal increased CC biomass yield by 63% in the first year compared with no removal. At the same site, late-terminated CC increased CC biomass yield by 16 times (0.15 vs. 2.44 Mg ha^{-1}) in the first year, by 11 times (0.19 vs. 2.03 Mg ha^{-1}) in the second year, and by 9 times (0.45 vs. 4.12 Mg ha^{-1}) in the third year compared with early-terminated CC.

Corn Growth and Yield

Residue removal affected corn height at both sites but CC had no effect. At the rainfed site, early in the growing season, corn under 0% removal was shorter (19.9 cm) than under 50% (21.7 cm) or 100% (25.2 cm) removal treatments. However, at tasseling, corn height did not differ among the residue removal treatments. At the irrigated site, early in the growing season, corn was taller (25.2 cm) in 100% than in 0% (19.9 cm) and 50% (21.7 cm) residue removal treatments. At tasseling, corn was similar in height across all treatments.

Residue removal had a significant effect on corn grain yield only at the irrigated site in the second year. Residue removal at 25, 75, and 100% increased grain yield by 11% compared to no removal (Table 5). Cover crop affected grain yield at both sites in the second year. Late-terminated CC reduced grain yield by 8% compared to no CC treatment. Across years, residue removal and CC termination date did not affect corn yield (Table 5). Residue removal and CC termination date had no effect on residue yield in any year or site. At the rainfed site, mean residue yield was 9.05 Mg ha^{-1} in 2014, 9.50 Mg ha^{-1} in 2015, and 11.0 Mg ha^{-1} in 2016. At the irrigated site, mean residue yield was 10.23 Mg ha^{-1} in 2014, 9.03 Mg ha^{-1} in 2015, and 11.30 Mg ha^{-1} in 2016.

Soil Temperature and Soil Water Content

Residue removal affected soil temperature for the measurement depth (5 cm) at both sites in May. Residue removal at 100% increased soil temperature by 1 to 3 °C at the rainfed site and by up to 5 °C at the irrigated site relative to the control in May. Residue removal and CC termination date did not affect soil water content at the rainfed site, but it affected soil water content in July at the irrigated site. At this site, complete residue removal reduced soil water content by 37% compared to the control in July.

Discussion

Water Erosion Potential

The results from this study showing a decrease in the size of water-stable aggregates with complete residue removal at the rainfed site and general decrease in size of water-stable aggregates at the irrigated site after 3 years suggest that excessive residue removal could increase water erosion potential (Figs. 1 and 2). Wet aggregate stability is a sensitive indicator of water erosion potential [2]. The reduction in soil aggregate stability at the rainfed site could be associated with the decrease in SOC concentration at this site (Table 3). The increased water erosion potential with complete residue removal at the rainfed site is similar to that reported in Kansas [19] and South Dakota [41].

The lack of strong differences in wet aggregate stability at the irrigated site in the short term suggests that irrigated soils could be more resilient to residue removal and could probably sustain greater amounts of removal without reducing soil structural quality and increasing water erosion risks. Similar to this study, a study in Kansas found no effects of residue removal on aggregate stability in two irrigated sites [19]. Collectively, our study and previous studies [19, 41] suggest that the level of residue removal from rainfed systems should be lower than from irrigated sites.

The increase in wet aggregate stability with late-terminated CC and lack of change in wet aggregate stability between early-terminated CC and no CC at both sites strongly suggest that late-terminated CC can improve soil structural quality and reduce water erosion potential regardless of irrigation regime. The increased wet aggregate stability under late-terminated CC relative to early-terminated CC can be due to the greater biomass production under late-terminated CC (Table 4). The study results appear to suggest that there may be a minimum CC biomass yield needed to improve soil structure. Cover crop biomass yield across the 3 years was 0.51 Mg ha^{-1} under early CC termination and 1.61 Mg ha^{-1} under late CC termination. This suggests that CC biomass yield above 1 Mg ha^{-1} could increase soil aggregate stability and offset the effects of crop residue removal. Minimum CC biomass amount required to improve MWD may vary depending on site characteristics such as irrigation and soil texture. For example, our results appear to suggest that lower CC biomass yield is required to increase MWD in rainfed sites (2.25 Mg ha^{-1} averaged across 2015 and 2016), while more CC biomass yield could be needed in irrigated sites (>3.30 Mg ha^{-1} averaged across 2015 and 2016). Further studies evaluating threshold levels of CC biomass production needed to improve soil properties are warranted.

The results of increased soil structural quality (MWD) with late-terminated CC indicate that this CC management strategy could allow for greater levels of corn residue removal compared to no or early-terminated CC in both rainfed and irrigated systems. However, terminating CC early, 1 to 3 weeks before main corn crop planting, appears to have no effect on offsetting the corn residue removal effects on water erosion potential (Fig. 1b). Previous studies on early-terminated CC following residue removal have found mixed results with regard to soil aggregate stability. On a rainfed site in eastern South Dakota, CC did not affect wet aggregate stability after residue removal for 4 and 6 years [35, 41], but on an irrigated site in south central Nebraska, CC increase wet aggregate stability and ameliorate the residue removal effects [7]. The increased aggregate stability under the late-terminated CC at the rainfed site cannot be compared with other studies as data are not available. Overall, results suggest that, in rainfed and irrigated sites, late-terminated CC offer promise to ameliorate residue removal effects on wet aggregate stability, potentially allowing increased levels of residue removal.

The smaller MWD of soil aggregates at the irrigated than at the rainfed site (Fig. 2) was likely due to the following factors. First, soil textural class was silt loam at the irrigated site and silty clay loam at the rainfed site. The greater clay content in the rainfed site likely allowed for greater aggregate stability [32]. Second, the irrigated site was previously under ridge till and disked before establishment of the experiment, whereas the rainfed site was under no-till for 20 years prior to experiment initiation. Thus, tillage operations at the irrigated site probably disrupted soil aggregates, leading to lower aggregate size [33].

Soil Organic Carbon

Residue removal even at high rates (100%) appears not to reduce SOC concentration in rainfed and irrigated soils after 3 years. We expected that near-surface (5 cm) SOC concentration would have decreased rapidly with high (>50%) rates of residue removal as microbes would use older SOC as a substrate for energy due to the lack of fresh aboveground residue input [35]. Root-derived SOC possibly offset any decrease in SOC due to aboveground residue removal. Previous work indicates that only about 40% of the aboveground residues left on a field can be incorporated into SOC [32]. Most contributions to SOC originate from roots [42]. Despite much of the root contribution to SOC, estimates show that excessive residue removal can consistently reduce SOC storage in corn production systems [21], but our experimental data after 3 years of residue management do not support such estimates. The trend for decreased SOC concentration with residue removal (Table 3) and the trend for increased SOC concentration with CC (Table 3) suggest that CC could partly offset residue removal effects on SOC, but long-term monitoring of SOC in these ongoing experiments is required for definitive conclusions. Results from this study are similar to previous field studies, which showed trends for increased SOC in both rainfed and irrigated sites [7, 35, 41].

Results showed that SOC concentration was unaffected by residue removal, including 100% removal of corn residues after 3 years, which suggests that, in the short term, even high rates of residue removal do not reduce SOC concentrations. Long-term monitoring is needed to determine the length of time at which complete removal could reduce SOC concentration in these and similar soils. The soil organic matter concentration was 4.8% (48 g kg^{-1}) at the rainfed site with <3% slope and 4.3% (43 g kg^{-1}) at the irrigated site with <1% slope. These levels of soil organic matter are higher than those in marginally productive or degraded croplands. Some studies have suggested that at least 5.25 Mg ha^{-1} of residues per year is needed to maintain SOC levels [42]. This study suggests that, in the short term, even complete removal of aboveground residues may not reduce SOC levels. As discussed earlier, root-derived SOC can be a major factor that offsets the aboveground residue removal effects. However, we hypothesize that continued residue removal at high rates could reduce SOC levels.

Since POM is a precursor to SOC, it could respond to residue management changes sooner. We expected that residue removal, especially at high rates, could reduce POM concentration because microbes continually use this as a substrate, but in our study, we observed no changes in POM concentration except with late-terminated CC at the irrigated site. The increase in POM concentration with late-terminated CC at the irrigated site could be attributed to the greater biomass yield in the irrigated than in the rainfed site. A higher seeding rate was used in the irrigated site in the third year (Table 2). The increase in POM concentration with late-terminated and not early-terminated CC at the irrigated site is probably due to the lower biomass yield under early termination. A few studies showed mixed effects of CC on POM [7, 26].

Cover Crop Biomass Yield

The greater CC biomass yield with late-terminated than with early-terminated CC was due to longer growing time. In 2015 and 2016, warmer than average temperatures in November and March probably allowed for longer CC growing season, but limited precipitation November 2014 and March 2015 likely minimized the differences in biomass yield between early and late-terminated CC in 2015 (Tables 1 and 4). By contrast, the wetter and warmer weather in March 2016 likely contributed to the greater CC biomass yield in 2016 compared with the previous years (Table 4). Previous studies on CC termination also showed that late-terminated CC can yield more biomass compared to early-terminated CC [13, 15, 28].

The range in CC biomass yield in this study was similar to that reported by a modeling study on rainfed soils [15]. The magnitude of biomass yield difference between early- and late-terminated was greater in this field study than the modeled results [15]. This could be due to the difference in termination times between early and late CC, which were 1 to 3 weeks in this study and 1 week in the modeling study. Late-terminated CC biomass yield was greater at the irrigated site than at the rainfed site most likely due to the greater seeding rate and later termination date at the irrigated site.

Currently, there are no studies that have evaluated the interactive effect of different rates of residue removal on CC biomass yield; however, the increase in CC biomass yield with residue removal under late-terminated CC, in some years, was possibly due to better CC seed-soil contact and emergence of CC in residue removal plots. The greater CC biomass yield with residue removal under late-terminated CC relative to no removal suggests that late-terminated CC could provide significant surface cover and potentially supplant the corn residue benefits. The CC appears to perform better when corn residues are removed than with no removal, indicating that late-terminated CC benefits can be larger or more essential when residues are removed.

Corn Yield

The increase in corn yield in 1 year at the irrigated site and no changes in corn yield at the rainfed site indicate that residue removal effects on corn yield can be site- or year-specific. No effect of residue removal on corn yield at the rainfed site was likely due to adequate moisture during critical times of corn development (Tables 1 and 5). The higher than average rainfall in 2015 combined with generally warmer temperatures likely provided optimum conditions for corn growth, which resulted in higher yields than in other years. Results from the rainfed site are similar to those reported in Kansas, where residue removal increased corn yield in some years compared to no residue removal [19]. Results, however, differ from a study in Ohio where residue removal reduced corn yield in some years [5]. Similar studies have also shown that increasing rates of corn residue removal may or may not affect corn yield in rainfed locations [42, 43]. The site specificity of residue removal effects on corn yield could mean different levels of residue removal for each site.

The increase in crop yield with ≥25% residue removal at the irrigated site in one of the 3 years suggests that in years with adequate moisture during the growing season (Table 1), residue removal may increase yield in irrigated sites. Other field studies from irrigated sites also showed that residue removal can increase yield in some years [17, 19]. A study across three irrigated fields in eastern Nebraska found that residue removal at rates above 75% from no-till continuous corn increased yield compared to no residue removal [42]. Our results and those of others suggest that residue removal could generally be beneficial to corn yield in irrigated sites. A modeling study, however, suggested that corn yield may decrease in irrigated sites with residue removal potentially due to lower soil water content from increased evaporation, which may then prompt use of additional irrigation and diminish finite groundwater resources [32].

The 3-year study results showed that early-terminated CC compared to no CC did not affect corn yield in any year. Late-terminated CC reduced corn yield in 1 year, 2015, which was likely due to low rainfall during the early growth stages of the corn. In 2015, rainfall at the time of planting through 3 weeks after planting was about 2.5 cm week^{-1}; however, the last part of May and early June had low rainfall <1 cm week^{-1} when the young corn plants were actively growing. The decrease in corn yield in one out of 3 years could be due to water use by the CC and reduced soil temperature under CC residues. Measured soil water content at the time of corn planting in 2015 at the rainfed site showed that late-terminated CC under the 100% residue removal reduced volumetric water content by 37%. A 10-year study on an irrigated site near our experimental site showed early-terminated rye CC reduced silage yield in 4 of 10 years compared to no CC, potentially due to soil water use by the CC [13]. The loss of silage yield with CC use was particularly evident in drought years, and averaged across years, use of rye CC reduced silage yield [14]. Studies using CC showed that water use by the CC may impact yield in some years [8, 39].

Late-terminated CC may only have negative effects on grain yield in years with rainfall below average during corn establishment (Table 1). In some cases, the small reduction in corn yield may be irrelevant due to overall greater yields, as observed in this study (Table 5). There are few studies comparing early- and late-terminated CC effects on corn yield. Further, no study has evaluated residue removal and CC termination date interactions. One site in Maryland with late-terminated CC showed increased grain yield [13]. A study assessing a single termination date in Pennsylvania found that the use of CC did not affect yield when terminated about 1 week before planting corn [1].

Summary and Conclusions

This study comparing early- and late-terminated CC with different corn residue removal rates in rainfed and irrigated locations suggests that CC could increase levels of residue removal while preventing water erosion and potentially maintaining SOC. Early-terminated CC, due to low biomass yield, does not appear to allow increased levels of residue removal; however, late-terminated CC, with greater biomass production, could allow increased levels of removal. Late-terminated CC can offset residue removal-induced reductions in wet soil aggregate stability, leading to reductions in water erosion potential, regardless of irrigation regime. The increase in soil aggregation leads to fewer soil particles carried into surface waters by large rain events [3, 10, 19]. The reduction in water erosion could also mean reduced losses of nutrients and C, reducing risks of pollution to surface waters [3, 10, 19].While there was no effect of residue removal on POM at the irrigated site, late-terminated CC increased POM, which suggests that CC could theoretically offset losses of labile fractions of soil organic matter from residue removal.

Late-terminated CC could offset the effects of residue removal on water erosion potential without reducing corn yields except in years when dry periods occur during early corn development. Early-terminated CC did not appear to offset any negative effects of residue removal on soil properties. From a cost-benefit analysis standpoint, early-terminated CC may not provide the economic benefits as discussed in a modeling study [27], but late-terminated CC could provide benefits to soil. Late-terminated CC did reduce corn yield in one of 3 years, suggesting that CC termination date may need to vary from year to year in order to balance levels of removal and yields. Under the conditions of this study, it appears that, in the short term (3 years), complete residue removal does not adversely affect soil properties when CC is added after removal and terminated late. Previous studies have suggested that only 30 or 50%of residue can be removed, but our results appear to suggest that higher rates of removal can be possible in some soils, depending on initial SOC concentration and use of CC to ameliorate the negative effects of removal. Further long-term (>3 years) monitoring of residue removal and CC effects on soil properties is needed as changes may develop after three or more years of treatment imposition. Moreover, research on how CC seeding rate and termination date interactions influences CC effects on soil properties after residue removal is also needed. Overall, this 3-year study showed that late-terminated CC could offset residue removal-induced increases in water erosion potential and does not reduce corn yield in most years under the conditions of this study.

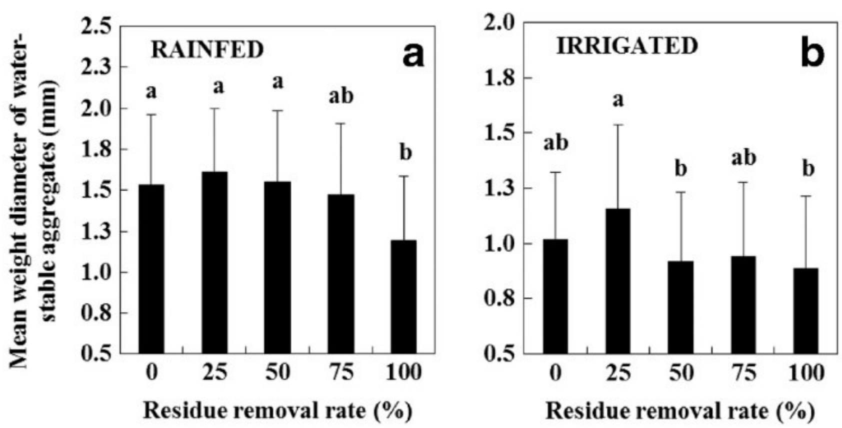

Fig. 1. Changes in mean weight diameter of water-stable aggregates under five corn residue removal rates at a rainfed site (a) and an irrigated site (b) in Nebraska. Data were collected in 2016. Differences for both sites were significant only at $p < 0.10$. *Different lowercase letters* indicate significant differences among residue removal rates. *Error bars* are the standard deviation of the mean.

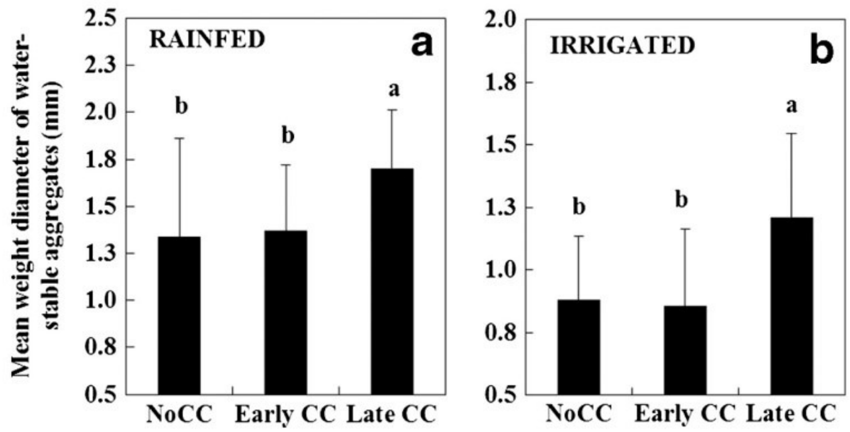

Fig. 2. Response of mean weight diameter of water-stable aggregates to three cover crop (*CC*) treatments [control (*no CC*), early-terminated CC (*early CC*), and late-terminated CC (*late CC*)] at a rainfed site (a) and an irrigated site (b) in Nebraska. Data were collected in 2016. *Different lowercase letters* denote statistical differences among CC treatments within a site. *Error bars* are the standard deviation of the mean.

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Conflict of interest — The authors declare that they have no conflict of interest.

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Tables follow . . . .

Table 1. Mean temperature and precipitation during the 2013–2016 study years for UNL's Rogers Memorial Farm (eastern Nebraska, rainfed) and South Central Agricultural Lab (south central Nebraska, irrigated). Irrigation amount listed in parentheses for the irrigated site.

	Mean temperature °C					Precipitation mm				
	2013	2014	2015	2016	30-year mean	2013	2014	2015	2016	30-year mean
Rainfed site										
January	−3	−5	−2	−4	−4	10	0	0	10	19
February	−2	−5	−6	2	−2	0	0	0	10	35
March	2	3	6	9	4	30	0	0	50	55
April	8	10	12	13	11	110	80	60	120	72
May	16	18	16	17	17	170	100	210	210	123
June	22	22	22	25	22	50	160	120	90	113
July	23	22	24	25	25	10	10	90	160	110
August	23	24	22	23	23	40	120	120	160	94
September	21	18	21	21	18	60	170	340	80	75
October	11	12	14	14	11	110	60	10	40	55
November	3	1	7	8	−6	30	0	60	20	42
December	−6	0	1	−3	−3	0	30	130	0	25
Annual	10	10	11	13	10	620	730	1140	950	818
Irrigated site										
January	−4	−3	−1	−3	−3	10	10	20	10	10
February	−1	−5	−3	2	−2	30	10	10	40	12
March	3	3	7	8	4	60	0	10	10	45
April	8	11	12	12	10	70	60	63	133	64
May	16	17	15	16	22	140	76	151	173	114
June	22	22	22	25	45	30	176	230	5	95
July	24	23	24	25	25	40	43 (30)	56 (70)	64 (90)	94
August	23	23	23	23	24	80	179 (70)	32 (110)	60 (90)	93
September	21	18	21	20	21	30	49	40	66	64
October	11	13	14	14	11	120	30	37	6	50
November	3	1	7	8	4	30	10	50	20	32
December	−4	−1	1	−3	−2	0	10	50	40	15
Annual	10	10	12	12	13	640	700	750	530	688

Sources of data were NRCS Scan (https://www.wcc.nrcs.usda.gov/scan/) for the rainfed site and WeatherUnderground (https://www.wunderground.com/us/ne/harvard) for the irrigated site.

Table 2. Management details of the two experimental sites including a rainfed site (UNL's Rogers Memorial Farm) and an irrigated site (South Central Agricultural Lab) in eastern and south central Nebraska, respectively.

Year	Date	Field management operations
Rainfed site		
2013	25–29 October	Residue removal treatments applied
	1 November	Rye planted at 67.25 kg ha^{-1}
2014	26 March	Anhydrous ammonia applied at 182 kg ha^{-1}
	22 April	Early termination sprayed with glyphosate at 1.6 L ha^{-1}
	5 May	Corn planted at 80,000 plants ha^{-1} and 46.7 L ha^{-1} 10–34–0 starter applied
	15 May	Late termination sprayed with glyphosate at 2.04 L ha^{-1}
	20 May	Residual herbicide applied 7.72 L ha^{-1} Lumax; 0.58 L ha^{-1} 2-4,D
	19 June	Post-emerge herbicide applied 2.81 L ha^{-1} atrazine
	30–31 October	Residue removal treatments applied
	31 October	Rye planted at 67.25 kg ha^{-1}
2015	17 March	Anhydrous ammonia applied at 182 kg ha^{-1}
	11 April	Early termination sprayed with glyphosate at 2.05 L ha^{-1}
	30 April	Corn planted at 80,000 plants ha^{-1} and 46.7 L ha^{-1} 10–34–0 starter applied
	31 April	Late termination sprayed with glyphosate at 2.04 L ha^{-1} and residual herbicides 7.72 L ha^{-1} Lumax; 0.58 L ha^{-1} 2–4,D
	18 June	Post emerge herbicide applied 2.81 L ha^{-1} atrazine
	27–29 October	Residue removal treatments applied
	30 October	Rye planted at 67.25 kg ha^{-1}
2016	21 March	Anhydrous ammonia applied at 205 kg ha^{-1}
	4 April	Early termination sprayed with glyphosate at 2.05 L ha^{-1}
	12 April	Residual herbicide applied Corvus at 0.41 L ha^{-1}
	26 April	Corn planted at 80,000 plants ha^{-1} and 46.7 L ha^{-1} 10–34–0 starter applied
	9 May	Late termination sprayed with glyphosate at 2.04 L ha^{-1}
	13 June	Post emerge herbicide applied 2.81 L ha^{-1} atrazine and 0.58 L ha^{-1} 2-4,D
	24–27 October	Residue removal treatments applied
Irrigated site		
2013	21 October	Residue removal treatments applied
	24 October	Rye planted at 56 kg ha^{-1}
2014	17 April	Early termination sprayed with glyphosate at 2.33 L ha^{-1}
	Late April	Fertilizer applied—liquid UAN coulter-banded between old rows
	7 May	Corn planted at 79,074 plants ha^{-1}
	9 May	Late termination sprayed with 7.01 L ha^{-1} Lexar and glyphosate at 2.33 L ha^{-1}
	21 and 28 October	Residue removal treatments applied
	30 October	Rye planted at 67.25 kg ha^{-1}
2015	13 April	Early termination sprayed glyphosate at 3.51 L ha^{-1}
	30 April	Fertilization with 224 kg N ha^{-1} liquid UAN coulter-banded
	1 May	Corn planted at 84,015 plants ha^{-1}
	5 May	Late termination sprayed with 7.01 L ha^{-1} Lexar and 4.68 L ha^{-1} glyphosate
	2 and 3 November	Residue removal treatments applied
	3 November	Rye planted at 112 kg ha^{-1}
2016	8 April	Early termination sprayed with glyphosate at 3.5 L ha^{-1}
	24 April	Fertilized with 247 kg N ha^{-1} liquid UAN coulter-banded
	5 May	Late termination sprayed with 2.92 L ha^{-1} glyphosate
	13 May	Corn planted at 84,015 plants ha^{-1}
	14 May	Late termination sprayed with 5.85 L Acuron ha^{-1} and 1.17 L ha^{-1} glyphosate
	13, 16, 17 October	Residue removal treatments applied
	31 October	Rye planted at 112 kg ha^{-1}

Table 3. Impact of five corn residue removal rates and rye cover crop termination dates on soil organic C, total soil N, and total particulate organic matter (POM) for the 0- to 5-cm depth at two sites in Nebraska.

Treatments (g kg soil^{-1})	Soil organic C (g kg soil^{-1})	Total soil N (mg g soil^{-1})	Total POM
Rainfed site			
Residue removal rate			
0	27.1	2.6	13.2
25	29.2	2.8	14.4
50	28.6	2.8	13.8
75	26.5	2.6	12.4
100	26.6	2.5	16.8
Cover crop treatment			
No cover crop	26.9	2.6	13.1
Early termination	27.3	2.6	15.4
Late termination	28.7	2.8	13.8
Parameter	*p* value		
Residue removal	0.53	0.46	0.61
Cover crop	0.46	0.14	0.57
Cover crop × residue removal	0.17	0.28	0.60
Irrigated site			
Residue removal rate			
0	25.5	2.6	15.7
25	25.1	2.5	15.3
50	25.2	2.8	14.2
75	24.5	2.8	16.1
100	25.2	2.5	13.9
Cover crop treatment			
No cover crop	23.9	2.5	14.3b
Early termination	26.0	2.7	14.5b
Late termination	25.4	2.7	16.4a
Parameter	*p* value		
Residue removal	0.97	0.48	0.20
Cover crop	0.26	0.59	0.027
Cover crop × residue removal	0.26	0.08	0.36

Data were collected in 2016. Different lowercase letters denote differences among cover crop treatments. No letter denotes no statistical differences.

Table 4. Impact of cover crop termination date and five corn residue removal rates on rye cover crop biomass yield at two sites in Nebraska.

Cover crop treatments	Residue removal rate (%)	Cover crop biomass yield (Mg ha^{-1})		
		2014	2015	2016
Rainfed site				
Early termination	0	0.023B	0.048B	1.03B
	25	0.029B	0.070B	1.93B
	50	0.030B	0.088B	1.28B
	75	0.042B	0.10B	1.30B
	100	0.033B	0.11B	1.50B
Late termination	0	0.20A	1.24bA	2.05bA
	25	0.43A	1.11bA	3.50aA
	50	0.35A	1.28bA	2.63abA
	75	0.25A	1.51bA	3.48aA
	100	0.39A	2.34aA	3.35aA
Parameter		*p* value		
Residue removal		0.17	0.007	0.03
Cover crop		<0.001	<0.001	<0.001
Cover crop × residue removal		0.15	0.002	0.31
Irrigated site				
Early termination	0	0.12bB	0.12B	0.37B
	25	0.12abB	0.12B	0.46B
	50	0.14abB	0.22B	0.32B
	75	0.16abB	0.24B	0.50B
	100	0.19aB	0.27B	0.58B
Late termination	0	2.68aA	1.50A	3.70A
	25	1.94bA	2.00A	4.29A
	50	2.61aA	2.32A	4.54A
	75	2.03abA	2.32A	4.07A
	100	2.92aA	1.99A	3.98A
Parameter		*p* value		
Residue removal		0.005	0.15	0.83
Cover crop		<0.001	<0.001	<0.001
Cover crop × residue removal		<0.001	0.30	0.86

Means with different lowercase letters indicate significant differences among residue removal treatments within a cover crop treatment and year. Means with different uppercase letters indicate significant differences between early and late-terminated cover crop treatments within a year.

Table 5. Mean corn grain yield under five corn residue removal rates and two rye cover crop termination dates at two sites in Nebraska.

Treatment	Grain yield (Mg ha^{-1}) 2014	2015	2016	Across years
Rainfed site				
Residue removal rate				
0	10.6	15.5	10.2	12.1
25	9.7	15.9	10.1	11.9
50	10.9	16.9	11.8	13.2
75	10.1	15.9	12.1	12.7
100	9.6	16.4	11.4	12.5
Cover crop treatment				
No cover crop	10.4	16.8a	11.0	12.7
Early termination	10.3	16.8a	10.5	12.3
Late termination	9.8	15.4b	11.8	12.3
Parameter	*p value*			
Residue removal	0.28	0.30	0.37	0.53
Cover crop	0.56	0.05	0.26	0.75
Cover crop × residue removal	0.14	0.90	0.62	0.92
Irrigated site				
Residue removal rate				
0	16.4	14.8b	17.2	16.1
25	17.5	16.4a	16.8	16.9
50	16.7	15.7ab	15.9	16.1
75	17.3	16.9a	17.2	17.2
100	16.8	16.2a	17.0	16.7
Cover crop treatment				
No cover crop	17.2	16.5a	16.9	16.9
Early termination	17.1	16.1a	16.8	16.7
Late termination	16.6	15.4b	16.8	16.3
Parameter	*p value*			
Residue removal	0.37	0.0014	0.98	0.11
Cover crop	0.38	0.021	0.82	0.26
Cover crop × residue removal	0.78	0.59	0.76	0.98

Different lowercase letters indicate significant differences among treatments within the same study factor and year. No letter denotes no statistical differences.