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Sabrina J. Ruis
USDA-ARS

Humberto Blanco-Canqui
University of Nebraska-Lincoln, hblanco2@unl.edu

Paul J. Jasa
University of Nebraska at Lincoln, pjasa1@unl.edu

Glen Slater
University of Nebraska-Lincoln, gslater1@unl.edu

Richard B. Ferguson
University of Nebraska - Lincoln, rferguson1@unl.edu

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Sabrina J. Ruis [a,*], Humberto Blanco-Canqui [b], Paul J. Jasa [c], Glen Slater [d], Richard B. Ferguson [b]

[a] *USDA-ARS National Laboratory for Agriculture and the Environment, Ames, IA 50011, USA*
[b] *Department of Agronomy and Horticulture, Univ. of Nebraska-Lincoln, Lincoln, NE 68583, USA*
[c] *Department of Biological Systems Engineering, Univ. of Nebraska-Lincoln, Lincoln, NE 68583, USA*
[d] *South Central Agricultural Laboratory, Univ. of Nebraska-Lincoln, Clay Center, NE 68933, USA*

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ABSTRACT

Low or variable cover crop (CC) biomass production could limit CC benefits. Longer CC growing periods via late termination could increase CC benefits, especially under limited crop residue return. We studied whether early (2–3 wk before planting)- or late (at planting)-terminated winter rye (*Secale cereale* L.) CC maintains soil properties, crop yields, and farm income under 0%, 25%, 50%, 75%, and 100% corn (*Zea mays* L.) residue removal in rainfed and irrigated no-till in the U.S. Great Plains after 6 yr. Early-terminated CCs produced < 1 Mg ha^{-1} of biomass while late-terminated CCs averaged 1.6 Mg ha^{-1} at the rainfed site and 3.0 Mg ha^{-1} at the irrigated site. At the rainfed site, CC termination date did not affect soils, but $\geq$ 75% residue removal reduced soil organic matter (OM) fraction concentrations and 100% reduced mean weight diameter of water-stable aggregates (MWD) in the 0–5 cm depth. At the irrigated site, late-terminated CC increased MWD by 0.22 mm and OM concentration by 5.1 g kg^{-1} compared with no CC. At the same site, 100% residue removal reduced microbial biomass, while $\geq$ 50% removal reduced OM concentration by 7.6 g kg^{-1}, available water, and MWD by 0.75 mm relative to no removal. Cover crops only partially offset the adverse effects of residue removal if biomass production was 3 Mg ha^{-1} yr^{-1}. Corn yield was generally unaffected. High residue removal rates offset CC-induced reduction in net income. Overall, late-terminated CC partially maintains soil health indicators following residue removal and minimally impacts crop yields and economics.

1. Introduction

Cover crops (CCs) can potentially increase soil OM and thus improve soil health indicators while providing other ecosystem services (Sanchez et al., 2019; Adetunji et al., 2020; McClelland et al., 2021; Haruna et al., 2022). However, the ability of CCs to improve soil health indicators may be linked to their biomass production, which may be variable in continuous corn or corn-soybean cropping systems due to the relatively short CC growing window in temperate regions (Ruis et al., 2017; Koehler-Cole et al., 2020; Ruis et al., 2020). Typical recommendations and practices for managing CCs in corn-based systems suggest terminating CCs up to 4 weeks in advance of planting the primary crop to avoid negative impacts on crop yields, although this varies with location (Bergtold et al., 2017; Plastina et al., 2020). When terminating the CCs at this stage, CC biomass production is typically low in cool temperate regions (Ruis et al., 2017; Reed et al., 2019; Chatterjee et al., 2020). For example, in the U.S. Corn Belt, early-terminated CC biomass production is often low (<1 Mg ha^{-1}) in corn-based systems, which can have limited effects on soil health indicators (Ruis et al., 2017; Chatterjee et al., 2020; Koehler-Cole et al., 2020).

One strategy to enhance CC biomass production might be terminating the CC late or at primary crop planting although it may have negative impacts on crop yield due to water use in dry years and nutrient immobilization (Reed et al., 2019; Blanco-Canqui et al., 2021). Few have evaluated the impacts of early- vs late-terminated CCs on soils and crop production. Terminating CCs late generally increases CC biomass production, but how this increased biomass production impacts soil properties and subsequent crop yields is still unclear. One of the few studies reported late-terminated CCs increased soil wet aggregate stability and particulate organic matter (POM) concentration relative to early-terminated CCs and had limited effects on crop yield (Ruis et al., 2017).

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* Corresponding author.
E-mail address: sabrina.ruis@usda.gov (S.J. Ruis).

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One of the benefits of the increased CC biomass production is its potential to offset negative impacts of other agricultural practices, such as crop residue removal. Crop residue removal for animal feed, bedding, and other uses is relatively common worldwide (Schinde et al., 2022). In the U.S. Great Plains and Midwest, baling of corn residue comprises about 17% of the planted area in the US Corn Belt (Schmer et al., 2017). The concern with corn residue baling is that it removes at least 50% of the residue meant to protect the soil from harvest in fall through planting in spring leading to increased water and wind erosion potential (Kenney et al., 2015). This high rate of residue removal can lead to detrimental effects on soil health indicators, particularly, soil aggregation and soil C (Wegner et al., 2015; Wegner et al., 2018; Sindelar et al., 2019a).

Adding CCs may have the potential to maintain soil health indicators after corn residue removal provided that CCs produce sufficient biomass such as via late CC termination. Few have studied this, particularly in the medium-term while also reporting CC biomass production (Table 1). The studies in Table 1 show that high rates of residue removal generally reduce POM concentration, water infiltration and water retention, and soil structural quality as measured by wet-aggregate stability, but CCs generally had mixed or no effect on such soil properties. Collectively, the few data suggest CCs may not always offset the adverse effects of excessive crop residue removal.

One of the mechanisms for the lack of CC effects on soil health parameters in Table 1 could be low (<1 Mg ha^{-1}) biomass production. However, if CCs were allowed to grow for longer periods, CC biomass production could be larger with greater effects on soil health indicators. Indeed, one study showed terminating a CC late (1.61–2.86 Mg ha^{-1} CC biomass) increased wet aggregate stability by 27%, while complete residue removal reduced this soil property by 29% relative to no and early-terminated CC (Ruis et al., 2017). These findings suggest CCs may be able to maintain soil health following residue removal if biomass is sufficiently large. Additional studies investigating the impacts of early- and late-terminated CCs combined with a gradient in corn residue removal rates on soils and crop yields in the medium- (5–10 yr) and long- (>10 yr) term are needed.

The use of CCs incurs a cost due to planting, seed, and potential reductions in yields. Studies evaluating the economics of CC use show implementing CCs has a financial penalty unless the CC is for alternative uses (i.e., grazing or haying) (Zhou et al., 2017; Holman et al., 2018; Plastina et al., 2020; Duncan et al., 2022). Pairing the CCs with crop residue removal may offset the CC implementation costs due to the income from sale of the crop residue. For example, if corn residue is worth \$84–367 ha^{-1} and CCs cost \$84–155 ha^{-1} for planting and seed, the farmer would gain \$0–212 ha^{-1} (Archer et al., 2014; Bergtold et al., 2017). To date, no study has evaluated the economics of different CC termination dates paired with crop residue removal at different rates. Thus, the objective of this study was to determine if early (2–3 wk before corn planting)- or late (at corn planting)-terminated winter rye CC can maintain soil health, crop yields, and farm income following corn residue removal (0%, 25%, 50%, 75%, and 100% removal rates) after six years of treatments in rainfed and irrigated no-till continuous corn in the eastern U.S. Great Plains. Our hypothesis was that late-terminated CC would maintain soil health indicators following moderate rates of residue removal with minimal impacts to crop yields and farm income.

Table 1
Literature review of the impacts of crop residue removal (RR) combined with cover crops (CC) on soil property and crop yield changes. The I denotes an increase, D denotes a decrease, and ns denotes no effect. SOC=soil organic C concentration, SOM=soil organic matter concentration; POM=particulate organic matter concentration.

Duration (yr)	Soil Property																Crop Yields		Reference
	Bulk Density		Cone Index		Wet-aggregate Stability		Water Infiltration		Water Retention		SOC/SOM		POM		Microbial Biomass				
	RR	CC	RR	CC	RR	CC	RR	CC	RR	CC	RR	CC	RR	CC	RR	CC	RR	CC	
3					D	I					D	ns	D	ns					Blanco-Canqui et al. (2014)
3	ns	ns			ns	ns					ns	ns							Blanco-Canqui et al. (2017)
3					D	I[‡]					ns	ns	ns	ns			ns	ns[§]	Ruis et al. (2017)
3					ns	I[‡]					ns	ns	ns	I[‡]			ns	ns[§]	Ruis et al. (2017)
5	ns	ns			ns	I					ns	ns	D	ns					Obrycki et al. (2018)
5											ns	ns					ns[¶¶]	ns[¶¶]	Adler et al. (2015)
5–6					D	ns	D	ns	D	ns	D	I[†††]							Sindelar et al. (2019a); b
6	ns	ns	ns	ns	D	ns	D	ns	D	ns	D	ns	D	ns	ns	ns	ns	ns	Current Study
6	ns	D	I	D	D	I	D	ns	D	ns	D	I	D	I	D	ns	ns	ns	Current Study
8																	I	ns	Schemer et al. (2020)
8, 3[¶]					D	ns					D	I[††]	D	ns	D[‡‡‡]	ns			Stetson et al. (2012); Hammerbeck et al. (2012)
9–12, 4–7																	D[‡‡]	D[‡‡]	Riedell et al. (2017)
10, 5					D	ns					D	ns	D[§§§]	I[§§§]	D[§§]	I[##]			Wegner et al., (2015, 2018)
12, 7					D	I					D	I	D	I					Osborne et al. (2014)
16, 5	I	D	I	D			D	I	D	ns	D	ns							Chalise et al. (2018)

[†] 100% removal reduced compared with rates ≤ 50%
[‡] Late-terminated CC increased, but not early-terminated CC compared with no CC
[§] No effect in 2 of 3 yr
[#] No effect in 2 of 3 yr
[¶] CCs introduced 5 yr after residue removal treatments began
[††] CC maintain following residue removal only, otherwise no effect
[‡‡] Soybean yield in dry years only
[§§] Microbial activity reduced following soybean
[##] Microbial activity increased following corn
[¶¶] Under continuous corn
[†††] When residue was removed
[‡‡‡] High rate of residue removal only
[§§§] During soybean phase only

2. Materials and methods

2.1. *Experiment sites, location, and design*

We used two study sites established during 2013 in Nebraska to accomplish our objectives. These two experiments were established at Rogers Memorial Farm near Lincoln, NE (40.846°N lat; −96.472°W long), which will be referred to as rainfed, and at South Central Agricultural Laboratory near Clay Center, NE (40.582°N lat; −98.144°W long), which will be referred to as irrigated. The soil at the rainfed site was an Aksarben silty clay loam (fine, smectitic, mesic Typic Argiudolls) with about 3% slope and at the irrigated site was a Hastings silt loam (fine, smectitic, mesic Udic Argiustolls) with < 1% slope. Mean annual precipitation was 818 mm and mean annual temperature was 10 °C for the rainfed site. Mean annual precipitation was 688 mm and mean annual temperature was 13 °C for the irrigated site. The monthly temperature and precipitation for the experiment period (2017–2019) are presented in Table 2. The irrigated site received 18.5 cm of irrigation in 2017, 14.3 cm in 2018, and 10.2 cm in 2019 primarily during Jul and Aug. Cover crops were never irrigated and both sites were under no-till. Data and management from 2013 to 2016 are presented in Ruis et al. (2017). The amount of growing degree days (GDD), during the CC growing period were calculated assuming a base temperature of 4.4 °C (Malone et al., 2022).

The experimental design was factorial with five corn residue removal rates (0%, 25%, 50%, 75%, and 100%) and three CC treatments (no CC, early-terminated CC, and late-terminated CC). There were four replicates for a total of 60 experimental units per site (5 removal rates × 3 CC treatments × 4 replications = 60 units). Plot sizes were 10 m by 10 m at the rainfed site and 10 m by 7.5 m at the irrigated site, both with 12 corn rows per plot. To achieve the different residue removal treatments, corn stalks were shredded at 10 cm height each fall and manually removed from select rows. For example, for 25% removal, residue was removed from three rows and the remaining nine rows of residue were redistributed among all 12 rows.

Cereal rye CC was drilled at rates of 67 kg ha^{-1} at the rainfed site in late Oct and 112 kg ha^{-1} at the irrigated site late Oct to early Nov (Table 3). The early-terminated rye CC was chemically terminated about two to three weeks before corn planting in mid-Apr at the rainfed site and in mid-Apr at the irrigated site. The late-terminated CCs were terminated at corn planting in late Apr to early May at the rainfed site and early to mid-May at the irrigated site. Corn was planted at 76,570

Table 2
Temperature and precipitation for experiment period (2013–2019) for both study sites in Nebraska. Irrigation amounts for the month are given within parenthesis. NA denotes not applicable as cover crops (CCs) were first implemented in fall 2013. Growing degree days (GDD) assumes a base temperature of 4.4 °C as per Malone et al. (2022).

Month	Temperature (°C)								Precipitation (mm)							
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**30-Year Mean**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**30-Year Mean**
	Rainfed Site															
Jan	-3	-5	-2	-4	-3	-6	-4	-4	10	0	0	10	26	5	10	19
Feb	-2	-5	-6	2	3	-5	-8	-2	0	0	0	10	11	13	13	35
Mar	2	3	6	9	6	4	1	4	30	0	0	50	73	65	57	55
Apr	8	10	12	13	12	6	12	11	110	80	60	120	45	9	26	72
May	16	18	16	17	16	20	15	17	170	100	210	210	186	83	213	123
Jun	22	22	22	25	23	24	22	22	50	160	120	90	153	138	110	113
Jul	23	22	24	25	25	24	25	25	10	10	90	160	70	146	76	110
Aug	23	24	22	23	21	23	23	23	40	120	120	160	64	101	80	94
Sep	21	18	21	21	20	20	22	18	60	170	340	80	90	179	132	75
Oct	11	12	14	14	13	10	9	11	110	60	10	40	142	82	114	55
Nov	3	1	7	8	5	1	3	-6	30	0	60	20	6	20	16	42
Dec	-6	0	1	-3	-2	-1	0	-3	0	30	130	0	3	84	62	25
Annual	10	10	11	13	12	10	10	10	620	730	1140	950	869	925	908	818
GDD of CC Period (Early Termination)	NA	248	271	598	420	164	231									
GDD of CC Period (Late Termination)	NA	486	417	695	565	311	361									
	Irrigated Site															
Jan	-4	-3	-1	-3	-3	-5	-2	-3	10	10	20	10	38	9	8	10
Feb	-1	-5	-3	2	3	-5	-7	-2	30	10	10	40	8	15	23	12
Mar	3	3	7	8	6	4	1	4	60	0	10	10	31	28	68	45
Apr	8	11	12	12	11	6	11	10	70	60	63	133	77	27	11	64
May	16	17	15	16	16	20	14	22	140	76	151	173	201	74	242	114
Jun	22	22	22	25	24	25	22	45	30	176	230	5	41 (72)	145 (22)	123	95
Jul	24	23	24	25	26	24	25	25	40	43 (30)	56 (70)	64 (90)	51 (62)	134 (83)	80 (64)	94
Aug	23	23	23	23	21	23	23	24	80	179 (70)	32 (110)	60 (90)	92 (51)	113 (37)	220 (38)	93
Sep	21	18	21	20	20	20	22	21	30	49	40	66	61	137	42	64
Oct	11	13	14	14	12	10	9	11	120	30	37	6	113	115	49	50
Nov	3	1	7	8	5	2	3	4	30	10	50	20	4	20	31	32
Dec	-4	-1	1	-3	-1	-1	0	-2	0	10	50	40	7	113	42	15
Annual	10	10	12	12	12	10	10	13	640	700	750	530	724	929	939	688
GDD of CC Period (Early Termination)	NA	244	323	346	450	198	244									
GDD of CC Period (Late Termination)	NA	464	527	546	629	499	476									

Table 3
Cereal rye planting and termination dates for the experimental period (2016–2019) for both study sites in Nebraska. Cereal rye cover crop planting and termination dates for 2013–2016 are given in Ruis et al. (2017).

Date	Field Operation
Rainfed Site	
27 Oct 2016	Cereal rye planted at 67 kg ha^{-1}
22 Feb 2017	Anhydrous NH_3 applied at 202 kg N ha^{-1}
11 Apr 2017	Early termination
5 May 2017	Corn planted at 76,570 seed ha^{-1}
27 Apr 2017	Late termination
31 Oct 2017	Cereal rye planted at 67 kg ha^{-1}
18 Mar 2018	Anhydrous NH_3 applied at 202 kg N ha^{-1}
14 Apr 2018	Early termination
28 Apr 2018	Corn planted at 76,570 seed ha^{-1}
4 May 2018	Late termination
30 Oct 2018	Cereal rye planted at 67 kg ha^{-1}
30 Mar 2019	Anhydrous NH_3 applied at 202 kg N ha^{-1}
19 Apr 2019	Early termination
26 Apr 2019	Corn planted at 76,570 seed ha^{-1}
3 May 2019	Late termination
Irrigated Site	
31 Oct 2016	Cereal rye planted at 112 kg ha^{-1}
17 Apr 2017	Early termination
9 May 2017	Corn planted at 83,980 seed ha^{-1}
9 May 2017	Late termination
13 Jun 2017	Fertilized with UAN at 225 kg N ha^{-1}
1 Nov 2017	Cereal rye planted at 112 kg ha^{-1}
23 Apr 2018	Early termination
30 Apr 2018	Fertilized with UAN at 225 kg N ha^{-1}
18 May 2018	Corn planted at 83,980 seed ha^{-1}
18 May 2018	Late termination
2 Nov 2018	Cereal rye planted at 112 kg ha^{-1}
23 Apr 2019	Early termination
26 Apr 2019	Fertilized with UAN at 225 kg N ha^{-1}
16 May 2019	Corn planted at 83,980 seed ha^{-1}
16 May 2019	Late termination

plants ha^{-1} at the rainfed site (Pioneer P1306W in 2017, P1477W in 2018, and DeKalb 62–00R1BW in 2019) and at 83,980 plants ha^{-1} at the irrigated site (DKC60–67 in 2017, 2018, and 2019). Corn was fertilized with pre-plant knifed anhydrous application at 202 kg N ha^{-1} annually at the rainfed site and with coulter-applied urea ammonium nitrate (UAN) at 225 kg N ha^{-1} at the irrigated site. Corn was harvested in mid- to late Sept at the rainfed site and mid-Oct at the irrigated site. Planting and termination dates for 2013–2016 are given in Ruis et al. (2017).

2.2. *Soil sampling and field data collection*

To assess CC termination date and corn residue removal rate impacts on soil properties, bulk soil samples were collected with a flat-bottom shovel from the 0–5 and 5–10 cm depth intervals in spring at the time of late termination in 2019 (6 yr after experiment initiation). Three soil samples were collected per plot. The bulk samples were used to assess soil health parameters of: wet aggregate stability, OM concentration, soil fertility properties, and microbial biomass and community structure. The bulk samples were air dried at 65 ºC for 3 d. Also, at the time of late termination, two stainless steel intact 5 cm diam. cores were collected from the 0–5 and 5–10 cm depth intervals. Intact cores were placed in plastic bags and stored at 4 ºC until analysis. Field data collection consisted of determination of soil sorptivity or initial water infiltration and cone index (compaction parameter) as described under Soil Physical Properties.

2.3. *Soil biological properties*

We assessed soil biological properties through microbial biomass and community structure. Phospholipid fatty acid analysis was conducted on the 0%, 50%, and 100% corn residue removal rates for the no, early-, and late-terminated CCs. Note that we assessed soil biological properties for three residue removal rates only as we were most interested in the CC effect. Air-dried samples were sieved through 2 mm and analyzed using the methods of Hamel et al. (2006). The microbial groups based on the fatty acids were: bacteria (sum of bacteria plus 19:0 iso, 19:0 anteiso), gram positive bacteria (14:0 iso, 15:00, 15:00 iso, 15:0 anteiso; 16:0 iso, 17:00, 17:0 iso, 17:0 anteiso), gram negative bacteria (10:0 2OH, 10:0 3OH, 11:0 2OH, 11:0 3OH, 11:0 iso 3OH, 12:2 OH, 12:0 3OH, 13:0 iso 3OH, 14:0 2OH, 14:0 3OH, 15:0 anteiso, 16:0 iso; 16:1 ω7c, 16:1 ω7 t, 16:1 ω9c; 16:0 2OH, 16:0 3OH, 16:1 2OH, 17:0 cyclo, 18:1 ω5c, 181 ω7c, 19:0 cyclo ω9, 19:0 cyclo ω9c, 19:0 cyclo ω6), actinomycetes (16:0 10-methyl, 17:0 10-methyl, 18:0 10-methyl), arbuscular mycorrhizal fungi (16:1 ω5c, 16:1 ω11c, 20:1 9c, 22:1 ω3c), saprophytic fungi (18:1 ω9c, 18:2 ω6,9c, 18:2, ω6c, 18:3 ω3c, 18:3 ω6c, 18:3, ω6c 6, 9, 12), and fungi (sum of fungi). The total microbial biomass was the sum of all components.

2.4. *Soil chemical properties*

Soil chemical properties were assessed through the determination of OM and POM concentrations, soil pH, concentrations of P, K, Mg, and Ca, and cation exchange capacity. Soil OM concentration was determined by loss on ignition using the methods of Nelson and Sommers (1996). The POM concentration was determined by the methods of Cambardella et al. (2001). Briefly, a 30 g, 2 mm sieved air-dried soil sample was dispersed with 5 g L^{-1} sodium hexametaphosphate for 24 hr on a reciprocal shaker. The dispersed soil was passed through a 53 μm sieve. Particulate organic matter left of the sieve was dried at 60 °C to constant weight and mass recorded. Samples were then heated to 450 °C in a muffle furnace for 4 hr and weighed. The amount of POM was then calculated as per Cambardella et al. (2001). Soil pH was determined using 1:1 soil:water slurry with a pH electrode (Peters et al., 2015). Soil P concentration was determined through extracting soil with Bray extract and determining concentration using colorimetric techniques against a standard curve (Frank et al., 2015). Concentrations of K, Ca, and Mg were determined on soil extracts with an atomic absorption spectrometer (Warncke and Brown, 2015). Cation exchange capacity was considered as the sum of K, Ca, Mg, and Na cations.

2.5. *Soil physical properties*

We determined soil physical properties through the measurement of sorptivity (initial water infiltration), cone index (compaction), bulk density, water retention and plant available water, thermal properties, and wet aggregate stability. To determine soil sorptivity, 9.75 cm diam. by 10 cm height steel rings were inserted into the ground at three locations within each plot. The time to complete infiltration of 75 mL of water was recorded and sorptivity calculated (Smith, 1999). We assessed soil penetration resistance using a cone penetrometer (Eijkelkamp Co., Giesbeek, the Netherlands; Lowery and Morrison, 2002) at ten locations per plot. The penetration resistance readings were converted to cone index. Cone index is commonly correlated with water content at the time of measurement, however, there was no correlation between water content and cone index at either site, thus no corrective equations were applied (Busscher et al., 1997; Blanco-Canqui et al., 2005).

To determine water retention, plant available water, and bulk density, intact cores were trimmed so top and bottom portions were flush with the ring surface and no soil remained on the outside of the core. Cheesecloth was secured with a rubber band at the bottom of the core to prevent soil loss. At the time of analysis, trimmed intact cores were slowly saturated from the bottom up for about 3 d. Water retention was determined at − 33 and − 1500 kPa. The intact soil cores placed on low suction pressure extractors until equilibration at − 33 kPa, which was considered field capacity for these soils (Klute, 1986).

After equilibration at − 33 kPa, we collected a soil subsample from each core for the determination of gravimetric water content, bulk density (Blake and Hartge, 1986), and volumetric water content. The remaining soil within the core was air-dried and passed through a 2 mm sieve. The 2 mm sieved soil was packed in 1 cm by 5 cm rings on a − 1500 kPa ceramic plate, allowed to saturate for 24 hr, and then placed in a high pressure extractor until equilibration (Dane and Hopmans, 2002). After equilibration at − 1500 kPa, the rings of soil were dried at 105 ºC for 24 hr to determine water content. Plant available water was the difference in water content at field capacity (−33 kPa) and permanent wilting point (−1500 kPa).

We assessed soil thermal conductivity using a KD2 Pro with SH-1 sensor (Decagon Devices, Pullman, WA) on the intact soil cores after equilibration at − 33 kPa. After weighing the core, the SH-1 sensor was carefully inserted into the core about 1 cm from the core edge until the sensor base touched the soil surface. The sensor was the left in the soil core for the manufacturer-programed measurement cycle.

Soil wet-aggregate stability was determined using the methods of Nimmo and Perkins (2002). Air-dried soil was sieved through an 8 mm sieve and 50 g of the sieved soil collected for analysis. The soil was placed on top of a stack of nested sieves with openings of 4.75, 2.00, 1.00, 0.50, and 0.25 mm. The top sieve contained filter paper to ensure soil aggregates wetted through capillary action. The soil was allowed to rewet through capillary action for 10 min, after which the filter paper was removed. The samples were mechanically sieved in an up and down motion for 10 min. Aggregates contained on each sieve were dried at 105 °C for 2 d and weighed. The mean weight diameter of water-stable aggregates (MWD) was calculated using the equations given by Nimmo and Perkins (2002).

2.6. *Yields and economics*

Cover crop biomass was harvested in mid-April for the early-terminated CC and in late April or early May for the late-terminated CC. The CC biomass was clipped at soil level from two 0.25 m^2 quadrats per plot. The biomass was air-dried at 65 °C for 3 d and weighed. The biomass yield was then scaled up to a Mg ha^{-1} basis.

In fall, corn ears and stalks were hand-harvested from two 2 m sections from the center two rows of each plot to determine grain and residue yield. Corn ears were removed from the stalk without removal of the husks and then stalks were cut at soil level. Both components were weighed in the field and three ears and three stalks selected at random for drying at 65 °C for 3 d before weighing. Grain was separated from the cob using a hand sheller. The masses of residue and grain were corrected for moisture content and scaled up to a Mg ha^{-1} basis. Note that grain yield was calculated at 15.5% moisture content (Ruis et al., 2017).

To assess the economic impacts of CC termination date and corn residue removal rate on farm economics, we combined site records of seeding rates (both corn and CC), herbicide rates and number of applications, and fertilizer rate and type with the Nebraska Crop Budgets for each year (Klein et al., 2014, 2015, 2016, 2017, 2018, 2019) along with USDA Crop Values from each year (USDA, 2014, 2015, 2016, 2017, 2018, 2019). The Nebraska Crop Budgets provide herbicide and fertilizer prices for each year along with the cost of each farm operation which includes labor, fuel and lube, repairs, and ownership costs. The rates for each farm operation, application rate and cost of application for herbicides and fertilizer, and general assumptions are provided in Supplementary Table S1–2.

2.7. *Statistical Analysis*

Before statistical analysis, the distribution of the data was checked for normality using the Shapiro-Wilk test in PROC UNIVARIATE in SAS (SAS Institute, 2022). Data were normally distributed and no transformations were performed. Soils data were analyzed by site and soil depth using PROC GLIMMIX in SAS for a randomized complete block design. The fixed factors were CC and corn residue removal rate and random factor was replication. Data on CC biomass, corn grain, and corn residue yields were analyzed by site and year following the same procedure as for soils data. We explored the relationships among CC biomass production, soil properties, corn grain yields, and number of days, total precipitation, mean temperature, and GDD accumulated during the CC period using PROC CORR in SAS. Treatment means were separated using least significant differences at the 0.05 probability level.

3. Results

3.1. *Cover crop biomass production*

Cover crop biomass production was affected by CC termination date at both sites and all years (Fig. 1A-B). Residue removal rate and the interaction of CC termination date × residue removal rate was significant in one year (2015) at the irrigated site and is discussed in a companion manuscript. At the rainfed site, the early-terminated CC produced 0.03–1.41 Mg ha^{-1} of biomass (0.47 Mg ha^{-1} average) and the late-terminated CC produced 0.19–4.24 Mg ha^{-1} (1.60 Mg ha^{-1} average). At the irrigated site, the early-terminated CC produced 0.11–0.60 Mg ha^{-1} (0.27 Mg ha^{-1} average) of biomass while the late-terminated CC produced 1.29–4.64 Mg ha^{-1} (3.04 Mg ha^{-1} average). Thus, late-terminated CC increased CC biomass by 1.13 Mg ha^{-1} at the rainfed site and 2.77 Mg ha^{-1} at the irrigated site compared with early-terminated CC.

Cover crop biomass production was typically correlated with the number of days, total precipitation amount, mean temperature, and cumulative GDD during the CC growing period (Table 4). At the rainfed site, precipitation, temperature, and GDD were highly influential for CC biomass accrual, explaining 68–83% of the variability. At the irrigated site, all four parameters drove CC biomass production, but GDD during the CC period was the most influential, explaining 91% of the variability. Across both sites, GDD affected CC biomass to the greatest extent followed by temperature, precipitation, and number of days in the CC period.

3.2. *Soil biological properties*

Cover crop termination date had no effect on total microbial biomass or microbial community structure at either site or depth (Table 5, Supplementary Table 3). Residue removal rate affected total microbial biomass and microbial community structure at the irrigated site only. There was no CC termination date × residue removal rate interaction. At the irrigated site, only complete residue removal reduced total microbial biomass by 30% and total bacteria by 37% compared with 0% removal. However, at the same site, corn residue removal at rates ≥ 50% reduced total fungal biomass by 24–56%, arbuscular mycorrhizal fungi by 33–88%, and saprophytes by 22–45% compared with no removal. Residue removal had no effect on total microbial biomass and generally no effect on community structure for the 5–10 cm depth at the irrigated site (Supplementary Table 3).

3.3. *Soil chemical properties*

The impacts of CC termination date and corn residue removal on soil chemical properties were significant for the 0–5 cm depth (Table 6) but not for the 5–10 cm depth (Supplementary Table 4) at both sites. There was no CC termination date × residue removal rate interaction for any soil chemical property at either site. Cover crop termination effects varied by site and chemical property. At the rainfed site, CC termination date had minimal effects on soil chemical properties while residue removal rate affected OM and POM concentrations. Complete residue removal reduced OM concentration by 12 g kg^{-1}, while residue removal rates ≥ 75% reduced POM concentration by 6 mg g^{-1} compared with no removal.

At the irrigated site, both CC termination date and residue removal rate affected OM and POM concentrations, but residue removal also affected pH and concentrations of K and Mg. At this site, late-terminated

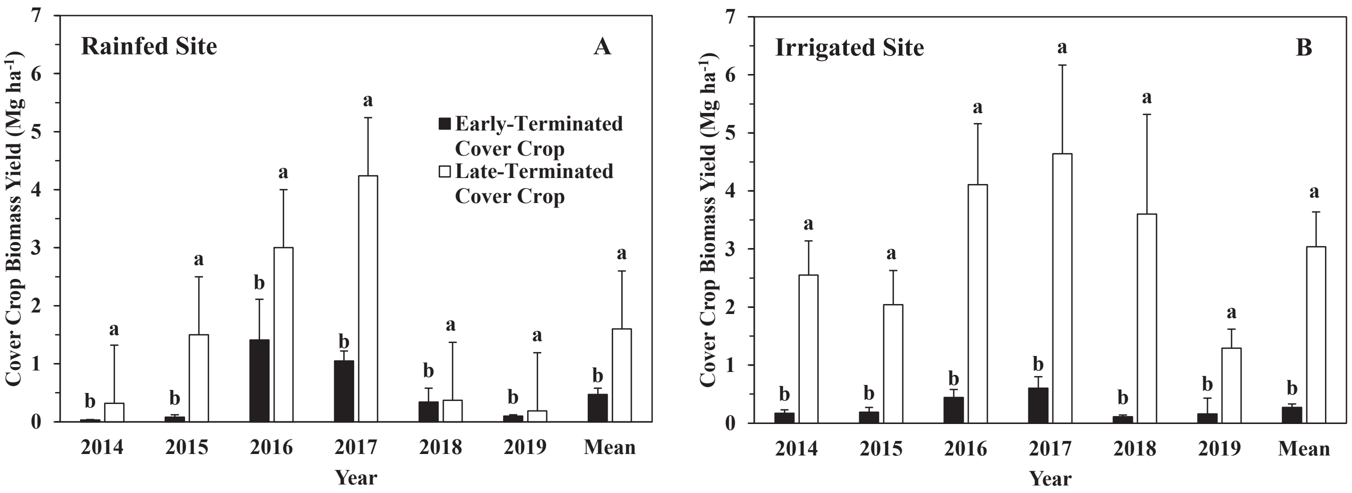

Fig. 1. Winter rye cover crop biomass production under early (2–3 weeks prior to corn planting) and late (at corn planting) termination at a rainfed (A) and an irrigated (B) site Nebraska for 6 yr (2014–2019). Means with the same lowercase letter within a year are not statistically significant at $p < 0.05$. Error bars are standard deviation.

Table 4
Relationships between cover crop (CC) biomass production and number of days, cumulative precipitation, average temperature, and growing degree days (GDD) during the CC growing period for two sites in Nebraska.

Site	Parameter	Equation	r	n	*p*-value
Rainfed	Number of Days	CCBiomass= $-2 \times 10^{-5} \times$ Days^2 + 0.03 ×Days-4.01	0.24	12	0.46
	Cumulative Precipitation	CCBiomass= 0.0055 × Precipitation - 0.45	0.68	12	0.015
	Average Temperature	CCBiomass= 0.52 × Temperature - 0.46	0.83	12	0.001
	GDD	CCBiomass= $7 \times 10^{-8} \times$ GDD$^{2.65}$	0.78	12	0.003
Irrigated	Number of Days	CCBiomass= 0.002 × Days^2-0.61 × Days + 47.65	0.80	12	0.002
	Cumulative Precipitation	CCBiomass= 0.0095 × Precipitation - 0.73	0.72	12	0.008
	Average Temperature	CCBiomass= 0.70 × Temperature - 0.54	0.75	12	0.005
	GDD	CCBiomass= $5 \times 10^{-10} \times$ GDD$^{3.56}$	0.91	12	< 0.001
Across Sites	Number of Days	CCBiomass= 0.0019 × Days^2-0.62 × Days + 50.77	0.60	24	0.002
	Cumulative Precipitation	CCBiomass= 0.0068 × Precipitation - 0.43	0.65	24	0.001
	Average Temperature	CCBiomass= 0.61 × Temperature - 0.47	0.77	24	< 0.001
	GDD	CCBiomass= $7 \times 10^{-9} \times$ GDD$^{3.09}$	0.79	24	< 0.001

CCs increased soil OM concentration by 5.5 g kg^{-1} and POM concentration by 6 mg g^{-1} compared with no and early-terminated CC (Table 6). In contrast, residue removal rates ≥ 25% reduced POM concentration by 10 mg g^{-1} and OM concentration by 7 g kg^{-1}. Also, residue removal rates ≥ 50% reduced K concentration by 68 mg kg^{-1}, rates ≥ 25% reduced Mg concentration by 25 mg kg^{-1}, and 100% removal reduced pH by 0.6 compared with no removal (Table 6).

3.4. Soil Physical Properties

Cover crop termination date and residue removal rate effects on soil physical properties varied by site and soil depth (Table 7, Supplementary Table 5). There was no CC termination date × residue removal rate interaction for any soil physical property at either site. At the rainfed site, CC termination date had no effect on any soil physical property at any depth. Corn residue removal, however, affected most soil physical properties in the 0–5 cm (Table 7) and not in the 5–10 cm depth (Supplementary Table 5). In the upper depth, complete (100%) residue removal reduced MWD by 0.54 mm, while corn residue removal at rates ≥ 75% reduced soil sorptivity (initial water infiltration) by 0.03 cm s$^{-1/2}$ compared with no removal. Residue removal at rates ≥ 25% reduced water content at − 33 kPa matric potential by 0.02–0.04 cm^3 cm^{-3}, water content at − 1500 kPa matric potential by 0.02 cm^3 cm^{-3}, and thermal conductivity by 0.20 W m^{-1} K^{-1} compared with no removal. Residue removal at rates ranging from 25% to 75% resulted in small reductions in soil bulk density, but residue removal rate had mixed effects on plant available water content.

At the irrigated site, CC termination date affected soil bulk density, cone index, MWD, water content at − 1500 kPa matric potential, and thermal conductivity in the 0–5 cm depth. Late-terminated CCs reduced bulk density by 0.1 Mg m^{-3} and thermal conductivity by 0.12 W m^{-1} K^{-1} compared with no and early-terminated CC. Late-terminated CC also increased MWD by 0.25 mm compared with no and early-terminated CC. Cover crop termination date had mixed effects on cone index and water content at − 1500 kPa matric potential. At the same site and depth, residue removal rate affected cone index, MWD, sorptivity, volumetric water content at − 33 kPa matric potential, and plant available water. Residue removal rates ≥ 25% increased cone index by 0.12 MPa and the amount of increase in cone index generally increased with increasing rates of residue removal. Residue removal rates ≥ 50% reduced MWD by 0.57–1.10 mm, ≥ 25% reduced water content at − 33 kPa matric potential by 0.02–0.05 cm^3 cm^{-3} and plant available water by 0.02–0.04 cm^3 cm^{-3}. Residue removal rates had mixed effects on sorptivity. At the 5–10 cm depth, CC termination date only affected cone index and MWD (Supplementary Table 5). Late-terminated CC reduced cone index by 0.03 MPa compared with no CC while early-terminated CC had no effect. Similarly, late-terminated CC increased MWD by 0.34 mm while early-terminated CC had no effect. Corn residue removal only affected cone index for the 5–10 cm depth where it increased cone index with increasing removal rates.

3.5. Corn yields and economics

Cover crop termination date and corn residue removal rate affected corn grain yield, but the effects varied by site and year (Fig. 2A-B). There was no CC termination date × residue removal rate interaction for corn grain yield. At the rainfed site, late-terminated CCs reduced crop yield

Table 5
Impacts of cover crop (CC) termination date and residue removal rate on soil biological properties (Mean±SD) in the 0–5 cm depth for both study sites in Nebraska. Means with the same lowercase letter within a main effect are not statistically significant at $p < 0.05$. Note that we assessed soil biological properties for three residue removal rates only. Entries in bold denote significant effects of treatments.

Treatment	Total Microbial Biomass (umol g^{-1})	Total Bacteria	Gram Positive Bacteria	Gram Negative Bacteria	Actinomycetes	Total Fungi	Arbuscular Mycorrhizal Fungi	Saprophytes
	Rainfed Site							
CC Treatment								
No CC	6.79 ± 2.31	3.23 ± 1.16	1.73 ± 0.63	1.52 ± 0.54	0.63 ± 0.23	0.99 ± 0.36	0.35 ± 0.15	0.64 ± 0.21
Early-Terminated CC	7.41 ± 2.28	3.53 ± 1.08	1.82 ± 0.57	1.72 ± 0.52	0.67 ± 0.20	1.11 ± 0.38	0.38 ± 0.14	0.73 ± 0.24
Late-Terminated CC	7.33 ± 2.61	3.48 ± 1.26	1.65 ± 0.77	1.72 ± 0.65	0.65 ± 0.20	1.10 ± 0.40	0.37 ± 0.14	0.72 ± 0.26
Residue Removal Rate								
0%	7.54 ± 2.57	3.58 ± 1.26	1.88 ± 0.67	1.70 ± 0.60	0.69 ± 0.24	1.11 ± 0.37	0.39 ± 0.14	0.71 ± 0.23
50%	7.28 ± 2.23	3.47 ± 1.06	1.66 ± 0.69	1.69 ± 0.56	0.65 ± 0.18	1.12 ± 0.40	0.39 ± 0.14	0.72 ± 0.27
100%	6.79 ± 2.39	3.37 ± 1.18	1.65 ± 0.60	1.57 ± 0.59	0.60 ± 0.22	0.97 ± 0.36	0.32 ± 0.14	0.65 ± 0.22
Parameter	*P* < F							
CC Treatment (CC)	0.63	0.46	0.58	0.39	0.82	0.46	0.63	0.39
Residue Removal Rate (R)	0.47	0.49	0.29	0.70	0.29	0.32	0.09	0.52
CC×R	0.01	0.01	0.003	0.04	0.004	0.03	0.01	0.04
	Irrigated Site							
CC Treatment								
No CC	5.62 ± 1.47	2.53 ± 0.71	1.44 ± 0.38	1.09 ± 0.34	0.50 ± 0.15	0.75 ± 0.24	0.25 ± 0.09	0.50 ± 0.15
Early-Terminated CC	5.14 ± 1.84	2.30 ± 0.90	1.29 ± 0.48	1.00 ± 0.43	0.45 ± 0.16	0.68 ± 0.31	0.22 ± 0.17	0.46 ± 0.19
Late-Terminated CC	5.97 ± 1.15	2.65 ± 0.58	2.62 ± 0.32	1.18 ± 0.27	0.46 ± 0.13	0.82 ± 0.17	0.26 ± 0.07	0.57 ± 0.11
Residue Removal Rate								
0%	**6.30 ± 1.28 a**	**2.86 ± 0.59 a**	2.69 ± 0.32	1.32 ± 0.28	0.47 ± 0.10	**0.92 ± 0.22 a**	**0.32 ± 0.08 a**	**0.61 ± 0.14 a**
50%	**5.59 ± 1.60 ab**	**2.53 ± 0.79 ab**	1.45 ± 0.45	1.08 ± 0.39	0.52 ± 0.18	**0.74 ± 0.22 b**	**0.24 ± 0.08 b**	**0.50 ± 0.14 b**
100%	**4.83 ± 1.36 b**	**2.09 ± 0.66 b**	1.21 ± 0.36	0.88 ± 0.30	0.42 ± 0.14	**0.59 ± 0.20 b**	**0.17 ± 0.07c**	**0.42 ± 0.13 b**
Parameter	*P* < F							
CC Treatment (CC)	0.26	0.37	0.39	0.32	0.60	0.20	0.49	0.09
Residue Removal Rate (R)	0.02	0.02	0.06	0.003	0.26	0.001	0.0004	0.003
CC×R	0.67	0.60	0.64	0.56	0.66	0.58	0.45	0.67

by 1.4–1.9 Mg ha^{-1} in only 2 of 6 years compared with no and early-terminated CC. Note that in one year, both early and late CC termination increased corn grain yield. Across the 6-yr study, early and late CC termination had no effect on corn grain yield. Corn residue removal rate only affected corn grain yield in one year and had no effect across years. Removal rates ≥ 75% reduced corn grain yield by 0.60 Mg ha^{-1} compared with 0% and 25% removal in 1 of 6 yr.

At the irrigated site, CC termination date affected corn grain yield in two years. In one year, late-terminated CC reduced corn grain yield by 1.11 Mg ha^{-1}, but in the other year, both early- and late-terminated CC reduced corn grain yield by 1.34–1.95 Mg ha^{-1}. Corn residue removal had no effect on corn grain yield in any year. Corn residue yield was unaffected by CC termination date and residue removal rate at both sites and all years. Corn residue yields ranged from 4.6 to 11.0 Mg ha^{-1} at the rainfed site and from 9.0 to 11.3 Mg ha^{-1} at the irrigated site.

Economic analysis and net income are summarized in Table 8. The CC termination date and residue removal treatments had effects on net income. At the rainfed site, early-terminated CCs reduced net income by \$39–385 ha^{-1} in 5 of 6 yr compared with no CC and late-terminated CC reduced net income by \$119–594 ha^{-1} in 4 of 6 yr. However, in 2 of 6 yr, late-terminated CCs had net income similar to no CC (within \$100 ha^{-1}). Net income generally increased with increasing residue removal rate, although there were similarities among removal rates depending on the year. Complete and 75% residue removal had similar net incomes in 1 of 6 yr and 100% removal had greater net income than 75% removal in 5 of 6 yr. In 2 of 6 yr, 0% and 25% had similar net income.

At the irrigated site, early-terminated CC reduced net income by \$125–410 ha^{-1} in all 6 years compared with no CC. Late-terminated CC also reduced net income by \$17–476 ha^{-1} in all 5 years compared with no CC. Similar to the rainfed site, the effects of residue removal at the irrigated site were generally highest under 100% removal and decreased with decreasing removal rate. In 5 of 6 yr, 100% removal had higher net income than 75%. In 2 of 6 yr, 50% removal had similar net income to 25% removal.

3.6. *Relationships among soil properties, corn yield, and cover crop biomass yield*

Table 9 shows the significance of the Pearson correlation coefficients among soil health parameters and mean CC biomass yield. At the rainfed site, total microbial biomass, bacteria biomass, fungi biomass, and organic matter concentration were moderately and positively correlated with plant available water (r = 0.34–0.35). The MWD was moderately and positively correlated with organic matter and POM concentrations

Table 6

Impacts of cover crop (CC) termination date and residue removal rate on soil chemical properties (Mean±SD) in the 0–5 cm depth for both study sites in Nebraska. Means with the same lowercase letter within a main effect are not statistically significant at $p < 0.05$. Entries in bold denote significant effects of treatments.

Treatments	Particulate Organic Matter (mg g^{-1})	Organic Matter (g kg^{-1})	pH	P (mg kg^{-1})	K	Ca	Mg	Cation Exchange Capacity (cmol kg^{-1})
	Rainfed Site							
CC Treatment								
No CC	24.9 ± 7.76	49.7 ± 5.3	6.8 ± 0.19	51.0 ± 7.34	561 ± 102	**2705 ± 157 a**	408 ± 114	**18.9 ± 2.01 a**
Early-Terminated CC	26.1 ± 6.87	48.5 ± 6.5	6.8 ± 0.35	46.2 ± 15.6	518 ± 97.3	**2633 ± 179 ab**	439 ± 122	**18.7 ± 1.89 a**
Late-Terminated CC	26.9 ± 8.60	49.7 ± 5.3	6.8 ± 0.13	49.6 ± 9.51	520 ± 62.9	**2570 ± 183 b**	403 ± 105	**17.7 ± 1.73 b**
Residue Removal Rate								
0%	**29.6 ± 6.76 a**	**53.8 ± 4.22 a**	**6.8 ± 0.12 ab**	50.0 ± 9.63	544 ± 105	2621 ± 199	409 ± 106	18.1 ± 1.58
25%	**26.4 ± 4.77 a**	**47.7 ± 5.12 b**	**6.7 ± 0.23 b**	49.8 ± 16.5	530 ± 87.2	2655 ± 129	466 ± 129	19.3 ± 2.03
50%	**27.3 ± 7.94 a**	**47.8 ± 3.71 ab**	**6.9 ± 0.22 a**	51.3 ± 9.95	528 ± 67.0	2642 ± 176	409 ± 128	18.5 ± 2.18
75%	**24.9 ± 8.96 b**	**48.6 ± 6.60 b**	**6.9 ± 0.18 a**	47.6 ± 8.77	542 ± 88.0	2652 ± 199	380 ± 94.7	17.8 ± 1.88
100%	**21.6 ± 8.23 b**	**42.2 ± 5.86 b**	**6.8 ± 0.35 ab**	45.9 ± 9.63	522 ± 86.6	2614 ± 162	421 ± 110	18.5 ± 1.84
Parameter	$P < F$							
CC Treatment (CC)	0.31	0.14	0.74	0.45	0.17	0.03	0.20	0.04
Residue Removal Rate (R)	0.002	0.01	0.05	0.65	0.96	0.95	0.06	0.20
CC×R	0.13	0.34	0.31	0.13	0.25	0.27	0.79	0.98
	Irrigated Site							
CC Treatment								
No CC	**24.2 ± 8.05 b**	**41.2 ± 5.40 b**	6.1 ± 0.41	117 ± 15.5	531 ± 73.3	2042 ± 154	259 ± 29.4	15.9 ± 1.01
Early-Terminated CC	**23.1 ± 8.14 b**	**40.5 ± 5.52 b**	6.0 ± 0.41	117 ± 13.5	520 ± 54.3	2024 ± 138	259 ± 24.4	16.2 ± 1.30
Late-Terminated CC	**30.0 ± 9.04 a**	**46.3 ± 7.20 a**	6.0 ± 0.47	118 ± 15.0	524 ± 91.1	1967 ± 126	254 ± 21.3	16.1 ± 1.09
Residue Removal Rate								
0%	**33.4 ± 8.98 a**	**48.0 ± 5.41 a**	**6.3 ± 0.33 a**	112 ± 11.9	**570 ± 58.2 a**	2103 ± 138	**277 ± 26.4 a**	16.0 ± 0.89
25%	**25.5 ± 7.75 b**	**43.8 ± 6.48 b**	**6.1 ± 0.41 a**	117 ± 13.9	**551 ± 79.4 ab**	1986 ± 178	**255 ± 25.9 b**	15.6 ± 1.12
50%	**24.6 ± 7.80 b**	**41.4 ± 4.29 b**	**6.1 ± 0.46 a**	111 ± 17.3	**502 ± 59.1 bc**	2008 ± 112	**254 ± 20.0 b**	15.8 ± 1.32
75%	**24.8 ± 9.43 b**	**43.9 ± 6.46 b**	**6.0 ± 0.41 ab**	121 ± 9.11	**515 ± 92.4 bc**	1998 ± 132	**257 ± 23.8 b**	16.1 ± 0.84
100%	**20.6 ± 5.60 b**	**36.0 ± 3.61c**	**5.7 ± 0.33 b**	126 ± 15.6	**490 ± 42.4c**	1961 ± 116	**243 ± 18.1 b**	16.8 ± 1.20
Parameter	$P < F$							
CC Treatment (CC)	0.01	0.005	0.46	0.93	0.88	0.18	0.67	0.74
Residue Removal Rate (R)	0.004	< 0.001	0.01	0.09	0.03	0.11	0.004	0.09
CC×R	0.58	0.46	0.30	0.52	0.73	0.99	0.92	0.20

($r = 0.39$–0.48). Particulate organic matter concentration was positively correlated with total microbial biomass and organic matter concentration with soil sorptivity. Grain yields by year were generally not correlated with CC biomass yield by year except in 2015 ($r = -0.32$; $p < 0.001$) and 2017 ($r = -0.42$; $p < 0.001$). Mean grain yield across years was moderately and negatively correlated with the mean CC biomass production ($r = -0.31$; $p < 0.05$).

At the irrigated site, total microbial biomass, bacteria biomass, fungi biomass, organic matter concentration and MWD were moderately and negatively correlated with cone index ($r = 0.27$–0.46). Total microbial biomass, bacteria biomass, and fungi biomass were positively correlated with sorptivity. Organic matter concentration was positively correlated with MWD, water content at − 33 kPa matric potential, and plant available water ($r = 0.32$–0.72). Fungi biomass was positively correlated with organic matter and POM concentrations, MWD, and sorptivity. Mean CC biomass production across years was moderately and positively correlated with organic matter and POM concentrations ($r = 0.31$–0.39), but negatively correlated with mean grain yield across years ($r = -0.34$; $p < 0.01$).

4. Discussion

4.1. Cover crop biomass production

As expected, late-terminated CCs increased CC biomass production (1.13 Mg ha^{-1} at the rainfed site and 2.77 Mg ha^{-1} at the irrigated site) at both sites compared with early termination, which is directly attributed to the longer CC growing period and improved weather conditions as time progresses in spring. For example, at the irrigated site, the highest CC biomass yields were achieved in years with above average temperature and rainfall (Table 2, Fig. 1). However, when temperature or rainfall was below average, then biomass yield was generally lower. At this site, above average temperatures with below average rainfall led to lower CC biomass production in the subsequent year. For example, in 2018, CCs produced > 3 Mg ha^{-1} when temperatures were above average and rainfall was below average. However, in 2019, CC biomass

Table 7

Impacts of cover crop (CC) termination date and residue removal rate on soil physical properties (Mean±SD) in the 0–5 cm depth for both study sites in Nebraska. MWD denotes mean weight diameter of water stable aggregates, VWC denotes volumetric water content, and PAW denotes plant available water. Means with the same lowercase letter within a main effect are not statistically significant at $p < 0.05$. Entries in bold denote significant effects of treatments.

Treatments	Bulk Density ($Mg\ m^{-3}$)	Cone Index (MPa)	MWD (mm)	Sorptivity ($cm\ s^{-1/2}$)	VWC at − 33 kPa ($cm^3\ cm^{-3}$)	VWC at − 1500 kPa	PAW	Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)
	Rainfed Site							
CC Treatment								
No CC	0.96 ± 0.10	0.74 ± 0.14	1.50 ± 0.48	0.09 ± 0.02	0.29 ± 0.02	0.19 ± 0.03	0.10 ± 0.03	0.88 ± 0.18
Early-Terminated CC	0.95 ± 0.13	0.68 ± 0.09	1.57 ± 0.48	0.10 ± 0.03	0.29 ± 0.02	0.20 ± 0.03	0.09 ± 0.03	0.87 ± 0.23
Late-Terminated CC	0.95 ± 0.08	0.66 ± 0.11	1.53 ± 0.47	0.10 ± 0.02	0.29 ± 0.03	0.20 ± 0.02	0.09 ± 0.03	0.86 ± 0.17
Residue Removal Rate								
0%	**1.04 ± 0.13 a**	0.67 ± 0.09	**1.82 ± 0.50 a**	**0.11 ± 0.02 a**	**0.31 ± 0.02 a**	**0.21 ± 0.03 a**	**0.10 ± 0.04 a**	**1.03 ± 0.24 a**
25%	**0.93 ± 0.07 bc**	0.69 ± 0.11	**1.65 ± 0.42 ab**	**0.11 ± 0.02 a**	**0.29 ± 0.01 b**	**0.20 ± 0.03 b**	**0.09 ± 0.03 ab**	**0.85 ± 0.15 b**
50%	**0.90 ± 0.10c**	0.69 ± 0.13	**1.41 ± 0.38 b**	**0.11 ± 0.03 a**	**0.29 ± 0.02 bc**	**0.19 ± 0.02 b**	**0.11 ± 0.03 a**	**0.82 ± 0.15 b**
75%	**0.90 ± 0.07c**	0.70 ± 0.14	**1.52 ± 0.54 ab**	**0.09 ± 0.02 b**	**0.28 ± 0.02 cd**	**0.18 ± 0.03 b**	**0.09 ± 0.02 ab**	**0.77 ± 0.14 b**
100%	**0.99 ± 0.09 ab**	0.72 ± 0.12	**1.28 ± 0.38c**	**0.07 ± 0.01 b**	**0.27 ± 0.02 d**	**0.19 ± 0.01 b**	**0.08 ± 0.02 b**	**0.87 ± 0.20 b**
Parameter	*P* < F							
CC Treatment (CC)	0.96	0.07	0.71	0.32	0.75	0.92	0.60	0.91
Residue Removal Rate (R)	0.001	0.77	0.001	0.0002	< 0.001	0.004	0.02	< 0.001
CC×R	0.91	0.17	0.31	0.05	0.26	0.37	0.11	0.88
	Irrigated Site							
CC Treatment								
No CC	**0.97 ± 0.07 a**	**0.66 ± 0.11 ab**	**1.18 ± 0.61 b**	0.049 ± 0.008	0.25 ± 0.03	**0.13 ± 0.02 ab**	0.12 ± 0.03	**0.84 ± 0.15 a**
Early-Terminated CC	**0.95 ± 0.08 a**	**0.69 ± 0.15 a**	**1.12 ± 0.39 b**	0.051 ± 0.009	0.24 ± 0.03	**0.13 ± 0.02 a**	0.11 ± 0.03	**0.82 ± 0.11 a**
Late-Terminated CC	**0.86 ± 0.09 b**	**0.61 ± 0.08 b**	**1.40 ± 0.54 a**	0.051 ± 0.011	0.24 ± 0.02	**0.12 ± 0.02b**	0.12 ± 0.03	**0.71 ± 0.17b**
Residue Removal Rate								
0%	0.93 ± 0.11	**0.56 ± 0.05c**	**1.72 ± 0.52 a**	**0.053 ± 0.01 a**	**0.27 ± 0.02 a**	0.13 ± 0.02	**0.14 ± 0.02 a**	0.80 ± 0.20
25%	0.92 ± 0.11	**0.64 ± 0.13b**	**1.50 ± 0.41 a**	**0.047 ± 0.004 b**	**0.25 ± 0.02b**	0.13 ± 0.02	**0.12 ± 0.03 b**	0.80 ± 0.18
50%	0.92 ± 0.06	**0.63 ± 0.09 b**	**1.15 ± 0.37 b**	**0.055 ± 0.008 a**	**0.24 ± 0.02 b**	0.13 ± 0.02	**0.11 ± 0.03 bc**	0.76 ± 0.12
75%	0.93 ± 0.06	**0.69 ± 0.09 ab**	**1.15 ± 0.38 b**	**0.051 ± 0.008 ab**	**0.23 ± 0.02c**	0.12 ± 0.02	**0.11 ± 0.03 bc**	0.79 ± 0.13
100%	0.93 ± 0.11	**0.74 ± 0.14 a**	**0.62 ± 0.18c**	**0.045 ± 0.004 b**	**0.22 ± 0.02c**	0.12 ± 0.02	**0.10 ± 0.03 c**	0.80 ± 0.13
Parameter	*P* < F							
CC Treatment (CC)	< 0.001	0.03	0.06	0.72	0.53	0.05	0.59	0.011
Residue Removal Rate (R)	0.99	< 0.01	< 0.0001	0.05	< 0.001	0.20	< 0.001	0.93
CC×R	0.42	0.51	0.62	0.95	0.43	0.50	0.25	0.59

production was the lowest of the 6-yr experiment, owing to warm, dry conditions the previous year combined with cool, wet conditions the following year.

The greater CC biomass production under late termination at the irrigated site relative to the rainfed site was probably due to a combination of factors including: 1) higher CC seeding rate, 2) longer CC growth period (19 d beyond early termination at the rainfed site and 25 d at the irrigated site), and 3) greater number of growing degrees accumulated. While all parameters (Table 4) influenced CC biomass production, the number of GDD tended to be the most influential and explained 78–91% of the data variability. This highly significant and strong correlation suggests calculation of GDD may be useful to inform CC termination timing. Thus, one could compute GDD already achieved during the CC period and then add the GDD for a 7–10 d forecast to determine if sufficient CC biomass would be present at a desired termination date. For example, using the equations in Table 4, the threshold GDD needed to achieve at least 1 Mg ha^{-1} of CC biomass was 501 °C days at the rainfed site, 410 °C days at the irrigated site, and 436 °C days across the two sites. Similarly, to attain 3 Mg ha^{-1} of CC biomass, 759 °C days were needed at the rainfed site, 558 °C days at the irrigated site, and 622 °C days across the two sites.

The amount of GDD needed to obtain a certain level of CC biomass production differed between the two sites likely because of other factors including CC seeding rate, soil texture, soil temperature (i.e., residue cover), and soil fertility. The lower GDD needed to achieve the same amount of CC biomass at the irrigated site compared with the rainfed

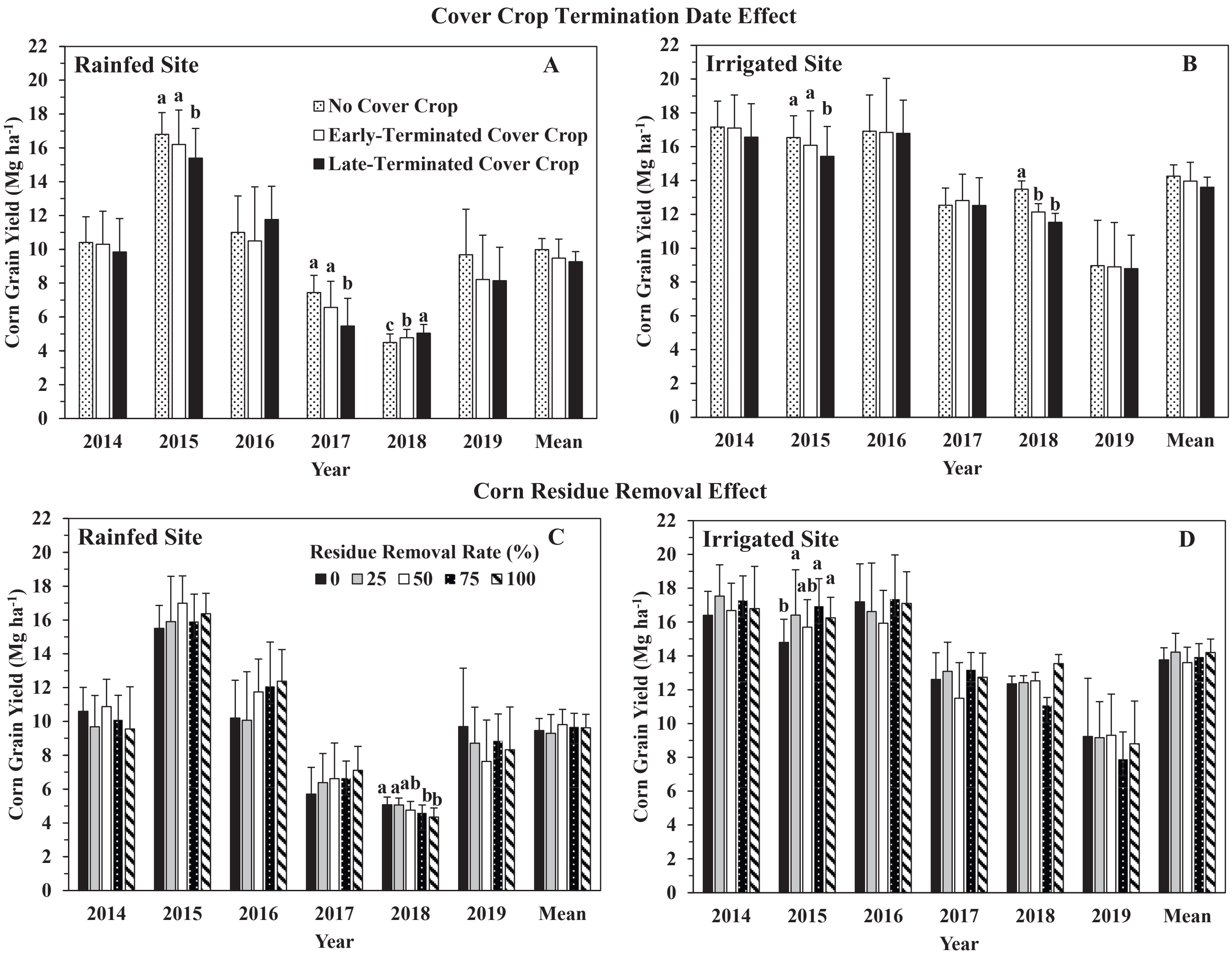

Fig. 2. Winter rye cover crop biomass production under early (2–3 weeks prior to corn planting) and late (at corn planting) termination at a rainfed (A) and an irrigated (B) site and corn residue removal rate impacts on corn grain yield in Nebraska for 6 yr (2014–2019). Means with the same lowercase letter within a main effect are not statistically significant at $p < 0.05$. Error bars are standard deviation.

site indicates fewer GDD may be needed to obtain the same level of biomass when seeding rates are higher. Of note, early-terminated CCs only accumulated 164–598 °C days (compared with 311–695 °C days for late-terminated). Thus, the additional 147–223 °C days accumulated by late-terminated CC can be critical to CC biomass production in this region. Indeed, observing the growing degree accumulation between early and late terminated CCs (Table 2) suggests substantial amounts GDD are accumulated between mid Apr and mid-May. Thus, if the annual average CC biomass input needed to improve soil health is about 3 Mg ha^{-1}, based on the response of soils at the irrigated site, then 622 °C days are needed during the CC period. Of note, at the rainfed site, in the two years when late-terminated CC biomass production was > 3 Mg ha^{-1}, 565–695 °C days were accumulated, which may indicate that GDD needs to be within this range at this site to achieve at least 3 Mg ha^{-1} of CC biomass.

The CC biomass production from the early-terminated rye CC was less than that reported by another study in the region (Acharya et al., 2017) due to earlier planting (mid Sep to mid Oct). However, biomass production under the late-terminated rye CC was greater than that reported by Adler et al. (2015), Sindelar et al. (2019a), and Schmer et al. (2020). Thus, terminating at corn planting and even delaying corn planting could be a strategy to boost CC biomass production in the study region or in climates and cropping systems similar to those in this study.

While another option to enhance CC biomass production is the interseeding of the CC before crop harvest, the need for timely rainfall and inconsistent CC germination and growth leads to low biomass production and few impacts on soil properties in the region (Koehler-Cole et al., 2020; Ruis et al., 2020).

4.2. Soil Biological, Chemical, and Physical Properties

One of the goals of this study was to assess whether or not early- or late-terminated CCs following corn residue removal at different rates can maintain soil health indicators in the medium-term (6 yr). The results after 6 yr show neither late- nor early-terminated CCs could improve or maintain soil health at the rainfed site due to the overall low mean biomass production (<1 Mg ha^{-1} for early termination and 1.60 Mg ha^{-1} for late termination). However, at the irrigated site, if CC grows for a longer period of about 25 d (i.e., late termination) relative to early termination, then the relatively higher CC biomass production (3.04 Mg ha^{-1} average) can partly offset the negative impacts of corn residue removal. Note that the degree of soil health maintenance following corn residue removal can depend on the soil health indicator and level of corn residue removal. There are three key considerations of using late-terminated CCs with corn residue removal on soil health: 1) the need for consistently high annual CC biomass production, 2) the time under

Table 8
Income, expenses, and net income under cover crops (CC) and different corn residue removal rates for both study sites in Nebraska from 2014 to 2019. See Supplementary Tables 1 and 2 for specific prices and rates.

Year	Treatment	Income From Corn Grain ($ ha^{-1})	Income From Stover	Corn Costs	CC Costs	Net Income	Income From Corn Grain ($ ha^{-1})	Income From Stover	Corn Costs	CC Costs	Net Income
		Rainfed Site					**Irrigated Site**				
2014	CC Treatment										
	No CC	1576	0	-797	0	779	2411	0	-895	0	1517
	Early-Terminated CC	1595	0	-797	-97	702	2383	0	-895	-97	1392
	Late-Terminated CC	1554	0	-797	-97	661	2491	0	-895	-97	1500
	Residue Removal Rate (%)										
	0	1577	0	-797	0	780	2411	0	-895	0	1516
	25	1486	205	-902	0	789	2723	250	-1009	0	1964
	50	1689	407	-925	0	1171	2430	463	-1037	0	1856
	75	1476	641	-952	0	1164	2578	705	-1070	0	2213
	100	1478	829	-974	0	1333	2571	999	-1101	0	2469
2015	CC Treatment										
	No CC	2161	0	-793	0	1368	2222	0	-988	0	1234
	Early-Terminated CC	2262	0	-793	-90	1379	2115	0	-988	-139	988
	Late-Terminated CC	2077	0	-793	-90	1194	1885	0	-988	-139	758
	Residue Removal Rate (%)										
	0	2161	0	-793	0	1368	2222	0	-988	0	1234
	25	2458	208	-916	0	1750	2348	211	-1113	0	1445
	50	2502	434	-943	0	1993	2263	397	-1139	0	1521
	75	2304	619	-965	0	1957	2448	607	-1173	0	1882
	100	2371	822	-999	0	2204	2306	816	-1196	0	1926
2016	CC Treatment										
	No CC	1252	0	-639	0	614	2306	0	-1018	0	1288
	Early-Terminated CC	1273	0	-639	-77	557	2208	0	-1018	-127	1064
	Late-Terminated CC	1333	0	-639	-77	617	2596	0	-1018	-127	1451
	Residue Removal Rate (%)										
	0	1252	0	-639	0	613	2306	0	-1018	0	1288
	25	1530	171	-761	0	940	2277	240	-1149	0	1368
	50	1447	391	-789	0	1049	2071	416	-1175	0	1312
	75	1494	541	-808	0	1226	2256	806	-1210	0	1851
	100	1457	728	-832	0	1352	2131	875	-1240	0	1766
2017	CC Treatment										
	No CC	906	0	-584	0	322	1696	0	-953	0	742
	Early-Terminated CC	586	0	-584	-65	-63	1574	0	-953	-102	518
	Late-Terminated CC	703	0	-584	-65	54	1632	0	-953	-102	577
	Residue Removal Rate (%)										
	0	906	0	-584	0	323	1696	0	-953	0	743
	25	1040	164	-688	0	515	1784	232	-1071	0	944
	50	1013	361	-705	0	669	1393	439	-1094	0	738
	75	933	453	-713	0	673	1644	610	-1119	0	1135
	100	935	613	-726	0	822	1604	998	-1152	0	1449
2018	CC Treatment										
	No CC	709	0	-574	0	134	1967	0	-857	0	1110
	Early-Terminated CC	734	0	-574	-64	95	1659	0	-857	-101	700
	Late-Terminated CC	823	0	-574	-64	185	1894	0	-857	-101	936
	Residue Removal Rate (%)										
	0	709	0	-574	0	134	1967	0	-857	0	1110
	25	730	113	-693	0	150	1903	274	-989	0	1189
	50	687	213	-700	0	200	1996	514	-1009	0	1502
	75	644	311	-707	0	248	1868	798	-1031	0	1636
	100	574	451	-717	0	309	2301	1006	-1051	0	2256
2019	CC Treatment										
	No CC	1794	0	-673	0	1121	1632	0	-908	0	724
	Early-Terminated CC	1747	0	-673	-64	1010	1454	0	-908	-101	444

(*continued on next page*)

Table 8 (*continued*)

Year	Treatment	Income From Corn Grain (\$ ha^{-1})	Income From Stover	Corn Costs	CC Costs	Net Income	Income From Corn Grain (\$ ha^{-1})	Income From Stover	Corn Costs	CC Costs	Net Income
	Late-Terminated CC	1264	0	-673	-64	527	1485	0	-908	-101	475
	Residue Removal Rate (%)										
	0	1793	0	-673	0	1120	1633	0	-908	0	725
	25	1483	256	-782	0	957	1515	199	-1021	0	693
	50	1525	528	-803	0	1249	1578	486	-1042	0	1022
	75	1417	788	-824	0	1381	1214	612	-1060	0	766
	100	1754	1060	-845	0	1969	1453	909	-1087	0	1275

management needed for CCs to maintain soil health following corn residue removal, and 3) the ability of CCs to maintain soil health following corn residue removal when the negative impacts of residue removal are larger than that of CCs.

Cover crop effects may be short-lived if biomass inputs are not consistent annually. For example, at these sites, MWD, POM concentration, and SOC concentration were determined after 3-yr of management (Ruis et al., 2017). At the rainfed site, late-terminated CCs increased MWD in year 3, but not after 6 yr. At the irrigated site, late-terminated CCs increased MWD and POM concentration after both 3 and 6 yr, and increased OM concentration after 6 yr. The lack of continued late-terminated CC impacts on soil properties at the rainfed site, but not at the irrigated site is likely related to differences in CC biomass input. At the rainfed site, CC biomass was low in two of three years (years 5–6) prior to sampling, unlike at the irrigated site. Cover crop C inputs are also transient in the soil and without consistent C inputs from the CC, much of the CC-derived C may be mineralized in the short-term (3-yr) (Austin et al., 2017), which can explain the lack of continued increase in soil properties between years 3 and 6 at the rainfed site (Ruis et al., 2017). Therefore, high levels of CC biomass production combined with sufficient time under CC management can lead to CC impacts on soils and could lead to the ability of CCs to maintain soil health following crop residue removal.

Corn residue removal rates $\leq$ 50% are often cited as “safe” levels of removal that have minimal impacts on soil properties (Wilhelm et al., 2004; Wilhelm et al., 2007). However, at both sites, 50% residue removal often had negative impacts on soils, thus without a support practice, degraded soil health is a concern. At the rainfed site, all rates of residue removal had negative impacts on organic matter concentration, volumetric water content at $-$ 33 kPa matric potential, and thermal conductivity, indicating no “safe” rate of residue removal exists for these soil properties at this site. At this site, $\leq$ 25% residue removal for MWD and $\leq$ 50% for sorptivity could be considered “safe” removal rates for these soil properties, although the negative impacts on other soil properties must be considered. Of note, residue removal resulted in small reductions in bulk density, probably due to the lack of insulating cover during winter freeze-thaw cycles. Since CCs did not affect soil properties at the rainfed site due to inconsistent and low biomass production, CCs do not appear to be able to maintain soil health following any rate of crop residue removal under the conditions of the rainfed site.

At the irrigated site, there was no “safe” removal rate for soil fungi biomass, POM and C concentrations, field capacity at $-$ 33 kPa matric potential, and plant available water. However, $\leq$ 25% could be considered “safe” for MWD and $\leq$ 50% site “safe” for bacteria biomass. At this site, CCs are unlikely to maintain most soil properties after residue removal. There were, however, three soil properties that responded to both CC termination date and residue removal rate: POM and OM concentrations and MWD. Late-terminated CCs may partially maintain POM concentration at all levels of removal. For example, the late-terminated CCs increased POM concentration by 5.8 mg g^{-1} while 25% removal reduced by 7.9 g kg^{1} and 100% by 12.8 g kg^{-1}, suggesting late-terminated CC can maintain 45–73% of POM concentration depending upon the removal rate. The late-terminated CC improved OM concentration by 5.1 g kg^{-1} while 25% removal reduced by 4.2 g kg^{-1}, 50% by 6.6 g kg^{-1}, and 100% by 12.0 g kg^{-1}. Thus, late-terminated CC could enhance OM concentration by 121% following 25% removal and maintain OM concentration by 43–77% following 50–100% removal. Similarly, late-terminated CC improved MWD by 0.22 mm, but 50% residue removal reduced it by 0.57 mm and 100% removal by 1.10 mm, indicating the late-terminated CC may maintain only 20–39% of MWD following 50–100% residue removal. Thus, CCs may partially offset the negative impacts of residue removal on some soil properties if CC biomass is consistently high.

The limited ability of CCs, even a late-terminated CC with high biomass production, to maintain soil health following crop residue removal can be attributed to the relatively low CC residue input compared with that of corn. For example, CCs produced 21% of the biomass produced by corn at the rainfed site (1.6 vs 7.8 Mg ha^{-1}). At the irrigated site CCs produced 29% of the biomass produced by corn (3.0 vs 10.3 Mg ha^{-1}). The non-significant correlation among microbial biomass, most physical properties, and CC biomass production (Table 9) corroborates this hypothesis. Thus, if 50% of the corn residue is removed at either site, then CC biomass production must be 3.9–5.2 Mg ha^{-1} annually to offset the C-input lost by removing corn residue.

The loss of C-input, whether from residue removal itself or from lack of C replacement by CCs following residue removal often drives changes in soil properties. Soil microbial biomass, particularly soil fungi, were sensitive to the loss of fresh OM food sources. In the case of soil fungi, the reduction in high C:N ratio corn residues needed for fungal biomass can be more detrimental to fungi than bacteria (Malik et al., 2016). Our results are generally in line with other studies, which have shown CCs may increase or have no effect on microbial biomass while residue removal may reduce microbial biomass or activity (Wegner et al., 2015; Thapa et al., 2022). Soil C loss following crop residue removal is not uncommon (Table 1), but a CC with high biomass production may increase soil C pools (Tables 6, 9). The degradation in soil physical properties, which is also a common occurrence in the literature (Table 1) with high rates of residue removal, is probably due to: 1) the reduction in soil OM input from residues and 2) the loss of protective soil cover, which can absorb raindrop impact and reduce soil aggregate disintegration. Soil properties, particularly soil MWD generally correspond to changes in OM pools. Indeed, in this study, POM and total OM concentrations were strongly correlated with MWD at the irrigated site (Table 9). Overall, maintaining C-input through careful CC and crop residue management is key to maintaining soil health indicators in these systems.

4.3. *Crop yields*

Cover crop management and corn residue removal rate do not have adverse effects on corn yields in most years in this study (Fig. 2). In the few instances when the late-terminated CC reduced crop yields relative to no or early-terminated CC, it was in years where rainfall was below normal in the months around planting and crop establishment. This

Table 9
Pearson correlation coefficients among soil health parameters in the 0–5 cm depth for a rainfed site and an irrigated site in Nebraska. Entries in bold denote significant correlations. TMB=total microbial biomass, OM=organic matter concentration, POM=particulate organic matter concentration, BD=bulk density, CI=cone index, MWD=mean weight diameter, Sorp=sorptivity, FC=field capacity, PWP=permanent wilting point, PAW=plant available water, CCBiomass=mean cover crop biomass yield, TC=thermal conductivity. ns=non-significant. * ** = $p < 0.001$; * * = $p < 0.01$; * = $p < 0.05$.

	TMB (umol g^{-1})	Bacteria (umol g^{-1})	Fungi (umol g^{-1})	OM (g kg^{-1})	POM (mg g^{-1})	BD (Mg m^{-3})	CI (MPa)	MWD (mm)	Sorp (cm s$^{-1/2}$)	FC (cm^3 cm^{-3})	PWP (cm^3 cm^{-3})	PAW (cm^3 cm^{-3})	CCB (Mg ha^{-1})	TC (W m^{-1} K^{-1})
Rainfed Site														
TMB (umol g^{-1})	1													
Bacteria (umol g^{-1})	**0.99** * **	1												
Fungi (umol g^{-1})	**0.98** * **	**0.98** * **	1											
OM (g kg^{-1})	0.25	0.24	0.18	1										
POM (mg g^{-1})	**0.35** *	0.33	0.15	**0.41** * *	1									
BD (Mg m^{-3})	0.17	0.16	0.21	-0.04	0.06	1								
CI (MPa)	-0.20	-0.19	-0.18	-0.18	-0.23	0.02	1							
MWD (mm)	0.29	0.20	0.25	**0.39** * *	**0.48** * **	0.06	-0.14	1						
Sorp (cm s$^{-1/2}$)	0.23	0.27	0.17	**0.28** *	0.21	-0.10	**-0.29** *	**0.30** *	1					
FC (cm^3 cm^{-3})	0.27	0.25	**0.34** *	**0.32** *	0.23	**0.35** * *	-0.07	0.21	**0.28** *	1				
PWP (cm^3 cm^{-3})	-0.19	-0.18	-0.09	-0.10	-0.07	**0.52** * **	-0.20	0.01	-0.01	0.23	1			
PAW (cm^3 cm^{-3})	**0.35** *	**0.34** *	**0.34** *	**0.33** * *	0.24	-0.13	0.11	0.14	0.21	**0.60** * **	**-0.63** * **	1		
CC Biomass (Mg ha^{-1})	0.18	0.18	0.04	0.23	0.08	-0.01	-0.12	0.06	0.17	-0.12	-0.01	-0.09	1	
TC (W m^{-1} K^{-1})	0.33	0.31	0.26	0.19	0.10	**0.81** * **	0.11	0.20	0.07	**0.62** * **	**0.30** *	**0.27** *	-0.04	1
Irrigated Site														
TMB (umol g^{-1})	1													
Bacteria (umol g^{-1})	**0.99** * **	1												
Fungi (umol g^{-1})	**0.96** * **	**0.97** * **	1											
OM (g kg^{-1})	0.17	0.19	**0.33** *	1										
POM (mg g^{-1})	0.21	0.20	**0.35** *	**0.68** * **	1									
BD (Mg m^{-3})	0.02	0.05	-0.01	-0.25	-0.09	1								
CI (MPa)	**-0.42** *	**-0.45** * *	**-0.52** * *	**-0.34** * *	**-0.42** * **	0.03	1							
MWD (mm)	0.29	0.31	**0.43** * **	**0.72** * **	**0.60** * **	-0.11	**-0.40** * *	1						
Sorp (cm s$^{-1/2}$)	**0.48** * **	**0.44** * *	**0.45** * *	-0.04	0.08	-0.02	-0.05	0.05	1					
FC (cm^3 cm^{-3})	0.04	0.08	0.17	**0.39** * **	**0.47** * **	0.21	**-0.46** * **	**0.57** * **	-0.04	1				
PWP (cm^3 cm^{-3})	-0.04	-0.01	-0.01	0.05	0.05	**0.52** * **	-0.06	0.10	0.17	0.10	1			
PAW (cm3cm^{-3})	0.06	0.08	0.16	**0.32** *	**0.39** *	-0.12	**-0.36** * *	**0.44** * **	-0.13	**0.82** * **	**-0.48** * **	1		
CC Biomass (Mg ha^{-1})	0.12	0.09	0.15	**0.39** * *	**0.31** *	**-0.57** * **	**-0.27** *	0.22	0.01	-0.11	**-0.27** *	0.05	1	
TC (W m^{-1} K^{-1})	-0.23	-0.19	-0.22	-0.14	-0.10	**0.68** * **	-0.09	-0.09	-0.12	**0.38** * *	**0.29** *	0.17	**-0.40** * *	1

suggests that while CCs use soil water, they may not reduce it to levels below which rainfall may not offset the reduction in most years. Interestingly, in 2017 at the rainfed site, while late termination increased the CC biomass production to the highest level in the 6-yr period and reduced corn yield, the following year was a very dry spring, but the late-terminated CC significantly improved yield by 0.28–0.55 Mg ha^{-1}. This indicates that the CC residues can provide a mulching effect during dry years. The mean CC biomass production was negatively correlated with corn grain yield, indicating that even though the CCs may not significantly reduce yields in a given year, tendencies for reductions do occur. Two reviews showed that CCs may or may not reduce corn yields depending on CC management, soil fertility, climate, and other factors (Marcillo and Miguez, 2017; Deines et al., 2023). Studies reporting corn yields under CCs following residue removal are few. The few studies generally report no effect of CCs or residue removal on crop yields (Table 1).

4.4. Economics

Economic analysis was conducted based on mean grain and stover yields rather than for each plot and running statistical analysis as producers would look at the direct values for net income rather than the statistical analysis. Cover crops incur a direct cost from seed, planting, and equipment use; however, they also may indirectly incur costs through reductions in crop yields. In this study, early-terminated CCs did not significantly reduce yields in any year at the rainfed site and in 1 yr at the irrigated site, but there were numerical reductions of 0.1–1.47 Mg ha^{-1} under early termination. These numerical reductions or trends for reduced yields with early-terminated CCs led to net income reductions of $39–385 ha^{-1} ($110 ha^{-1} average) at the rainfed site and $125–410 ha^{-1} ($251 ha^{-1} average) at the irrigated site.

Regarding late termination, the late-terminated CCs reduced yields in two years at each site, but all remaining years showed trends for reduced yields which led to net income reductions of $119–594 ha^{-1} ($184 ha^{-1} average) at the rainfed site and $17–476 ha^{-1} ($153 ha^{-1} average) at the irrigated site. Thus, while CCs can induce non-significant reductions in yields, those non-significant reductions can equate to large net income losses. Of note in all years, net income was always above break-even or zero, even with late-terminated CCs. Other studies of net income following CCs also show that CCs may not offset their own implementation costs (Zhou et al., 2017; Holman et al., 2018; Singh et al., 2021). These studies report net income reductions of $38–176 ha^{-1}. The net income reductions from other studies are sometimes lower due to the study being conducted in a region with higher rainfall (i.e., lower yield reduction), not including a cover crop every year, or lower-value cash crops.

The results in Table 8 show that corn residue removal can increase net income at most residue removal rates and in most years. The level of increase ranged from $9–1146 ha^{-1}, although the 25% removal rate reduced net income by $32–164 ha^{-1} in some years due to the costs for stover chopping, windrowing, and baling being larger than the income received from selling the bales. Our residue removal calculations do not include bale storage or transport costs as these will greatly depend on the end use of the bales. For example, in some locations, the bales may be used within the farm for animal feed or bedding while in other locations the bales may be transported larger distances to biofuel refineries. Previous studies have not investigated how different rates of stover removal affect net income, but they have investigated different price points for the stover, transport distances, and other factors (Brechbill et al., 2011; Sesmero and Gramig, 2013; Archer et al., 2014;). Some have recommended stover prices of $26–73 Mg^{-1}, which is lower than our $77–97 Mg^{-1} prices which were based on the value of hay (Archer et al., 2014; Pratt et al., 2014). Lower values of stover will require higher levels of removal to break-even.

The question is, however, at what level of residue removal is the cost of CC implementation offset? Based on Table 8, at both sites, 25–50% residue removal is the minimum level of removal needed to offset the cost of cover crop implementation if the CC is terminated early. If the CC is terminated late, 50–75% removal is the minimum level of removal needed to offset CC implementation cost. Note that the profit margins are smaller under lower rates of residue removal than with higher. Thus, it appears that residue removal could be used to offset the cost of implementing the CC.

5. Conclusions

This study evaluating the impacts of CC termination date (early vs late) following corn residue removal at 0, 25, 50, 75, or 100% on soil health indicators (soil biological, chemical, and physical properties as indicators), corn yields, and economics after 6-yr of treatments at a rainfed and an irrigated site in the western US Corn Belt indicates the following:

- early-terminated CCs do not improve soil health and have minimal effects on corn yield while reducing net income.
- late-terminated CCs with consistently high biomass (~3 Mg ha^{-1}) can improve soil health indicators and generally have no effect on crop yields, but can reduce net income.
- the impacts of a late-terminated CC accumulate with time, but may also disappear if CC biomass production is not consistently high.
- moderate to high rates of corn residue removal can reduce or degrade soil health indicators while increasing net income with minimal impacts on corn yield.
- only CCs with consistently high biomass can partially offset the negative impacts of corn residue removal on soil health indicators.
- the concern with high-biomass producing cover crops is negative impacts on subsequent crop yields, yet our results suggest significant reductions in corn yield do not occur in most years.
- CCs reduce net income due to seed and planting costs, but residue removal of at least 25% can offset CC implementation costs and offset non-significant reductions in corn yield.

Residue removal must be balanced with the negative impacts to soils and the partial offset provided by CCs if biomass is sufficient. Our findings suggest that if improvements in soil health are desired and one wants to at least partially offset residue removal effects on soils, then terminating CCs late can be a potential management practice. Overall, if consistently high CC biomass is produced, late-terminated CC partially maintains soil health following corn residue removal with few impacts to crop yields and economics.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Humberto Blanco-Canqui reports financial support was provided by Nebraska Environmental Trust.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2023.109076.

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