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Cover crops and soil health in rainfed and irrigated corn: What did we learn after 8 years?

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Abstract

Duration of cover crop (CC) management, CC biomass production, and other factors could impact how CC affects soil health. We studied the 8-year cumulative impacts of winter rye (*Secale cereale* L.) CC on soil physical, chemical, and biological properties in rainfed and irrigated no-till corn (*Zea mays* L.)-based systems in the western US Corn Belt. Average annual CC biomass production was 0.56 ± 0.51 Mg ha^{-1} at the rainfed site and 0.98 ± 0.95 Mg ha^{-1} at the irrigated site. After 8 years, CC improved particulate organic matter (POM) and mean weight diameter of water-stable aggregates (MWD) compared with no CC in the 0–5 cm soil depth at both sites. Cover crop increased total POM concentration by 2.8 mg g^{-1} at the rainfed site and by 13.4 mg g^{-1} at the irrigated site, while it increased MWD by 0.39 mm at the rainfed site and by 0.79 mm at the irrigated site. Also, CC increased soil C at a rate of 0.125 Mg ha^{-1} year^{-1} in the 0–5 cm depth but only at the rainfed site. Cover crop affected neither water infiltration nor available water but improved microbial biomass. Changes in other properties were site-dependent. Cover crop improved many soil properties after 8 years even though measurement taken after 4 years showed no significant effect of CC, which indicates CC slowly impacts properties in this environment. Low CC biomass production and high biomass input from corn-based systems may explain the slow soil response. In general, winter rye CC enhances near-surface soil properties in the long term.

1 | INTRODUCTION

Cover crops (CCs) are considered an important management practice to maintain or improve soil properties and thus soil health and ecosystem services. Indeed, CCs are receiving increased attention for their long-term contributions to soil carbon (C) sequestration and adaptation of croplands to climatic fluctuations (Delgado et al., 2021; Guardia et al., 2019; Kaye & Quemada, 2017). For instance, a potential improvement in soil hydraulic properties after CC introduction, such as increased water infiltration and water-holding capacity, can contribute to precipitation capture and storage, adaptation to droughts, and reduction in runoff risks.

Abbreviations: CC, cover crops; POM, particulate organic matter; SOC, soil organic carbon; MWD, mean weight diameter of water-stable aggregates.

Available research information suggests, however, that CC impacts on soil physical, chemical, and biological properties can be rather inconsistent, depending on numerous factors (Ruis et al., 2020; Sindelar et al., 2019). These potential factors that affect CC performance have not been widely discussed. In some cases, CC enthusiasts presume that planting CCs would undoubtedly improve soil properties and health without considering site-specific conditions. Experimental data suggest that the extent to which CCs can impact soil properties can vary with soil type and historic land use, as not all soils have the same initial conditions nor are they under the same management strategies (Anderson et al., 2022; Blanco-Canqui, 2022; McClelland et al., 2021; Rorick & Kladivko, 2017; Sindelar et al., 2019).

Among the specific factors that can affect CC performance include CC biomass production, years after CC introduction, initial soil C level, cropping system, soil textural class, and irrigation management (rainfed vs. irrigated), among others (Blanco-Canqui, 2022; McClelland et al., 2021). For example, the ability of CCs to improve soil properties can be limited when CC biomass input is low. Studies have suggested that about 1 Mg ha^{-1} year^{-1} of CC biomass production may be needed to exert significant changes in soil properties (Koehler-Cole et al., 2020). The window of time for planting CCs could affect the amount of biomass produced by CCs. In cool temperate regions in corn (*Zea mays*)–soybean (*Glycine max*) systems, winter CCs are often planted in late fall after main crop harvest and terminated in early spring of the following year up to 4 weeks before planting main crops. Under such management conditions, CCs may not produce sufficient biomass to exert major changes on soil properties. For instance, in a review of CC studies in temperate regions, McClelland et al. (2021) reported that the length of total growing season for the CC was one of the top predictors of changes in soil organic C concentration.

Further, CCs may have small or no significant effects on soil properties in the short term (<5 years; Anderson et al., 2022; Rorick & Kladivko, 2017; Ruis et al., 2017). Cover crop biomass production fluctuates from year to year due to annual fluctuations in precipitation amount and temperature, and thus any benefits from CCs may not be detectable in the first few years (Koehler-Cole et al., 2020; Ruis et al., 2020). Yet, most available data on CCs and soil properties are currently from short-term (<5 years) experiments. Our understanding of how CCs perform in the medium- and long-term is still limited. Data from multiple years and multiple sites are needed to draw more definitive conclusions about CC effects on soil properties that determine the health of soils in a specific region.

Additionally, how irrigation of the main crop affects CC impacts on soil properties is unclear. Studies evaluating soil response to CCs in both rainfed and irrigated cropping systems are rare (Ruis et al., 2017). For example, irrigated no-till corn systems often leave larger amounts of corn residues compared to rainfed no-till corn systems, which could differently impact CC effects on soil properties. Also, irrigation of main crops planted after CC termination may accelerate CC residue decomposition compared to nonirrigated conditions. Yet most CC studies, particularly those reporting soil properties, have been conducted in rainfed systems and few in irrigated systems (Çerçioğlu et al., 2019; Rorick & Kladivko, 2017; Steele et al., 2012). The potential sources of variability in CC potential to alter the soil environment deserve further research under different CC management scenarios and environmental conditions. Thus, the objective of this paper was to assess 8-year cumulative impacts of winter rye (*Secale cereale* L.) CC on soil physical, chemical, and biological properties in rainfed and irrigated no-till corn-based systems in the western US Corn Belt.

Core Ideas

- Winter rye cover crop (CC) improved most dynamic soil properties in rainfed and irrigated systems after 8 years.
- Including CC in rainfed corn increased soil C at a rate of 0.125 Mg ha^{-1} year^{-1}.
- Water infiltration and plant available water did not change after 8 years of CC management.
- Soil properties significantly changed only after 8 years and not after 4 years due most likely to low CC biomass input.
- In general, winter rye CC can enhance near-surface soil properties in the long term.

2 | MATERIALS AND METHODS

2.1 | Sites and experimental design

To accomplish our objectives, we conducted this analysis in spring 2022 using data from two experiments in Nebraska after 8 years of CC treatments. The two experimental sites were established in fall 2014 at the University of Nebraska's Eastern Nebraska Research, Extension, and Education Center near Mead (41°09′N, 96°24′ W) and South Central Agricultural Laboratory near Harvard (40°34′ N, 98°08′ W). The site near Mead will be referred to as rainfed while the site near Harvard will be referred to as irrigated. The soils were Tomek (fine smectitic, mesic Pachic Argiudolls) and Filbert (fine, smectitic, mesic Vertic, Argiabolls) silt loams at the rainfed site and a Hastings silt loam (fine, smectitic, mesic Udic Argiustolls) at the irrigated site. The weather conditions during the experimental period and long-term weather averages are shown in Table 1. The weather data were collected from the High Plains Regional Climate Center using stations near Mead for the rainfed site and Clay Center for the irrigated site.

The two experiments were established under no-till in a randomized complete block with three replications. The treatments were: winter rye CC and no CC at both sites. There were two cropping systems at the rainfed site, including corn–soybean and continuous corn, while there was only one cropping system (corn–soybean) at the irrigated site. The plot sizes were 4.5 × 9 m at the rainfed site and 6 × 9 m at the irrigated site. The winter rye CC was broadcast seeded at 300 seed m^{-2} in fall into the standing crops at the rainfed site and drilled after main crop harvest at the irrigated site. The CC was chemically terminated in spring 1–4 week before corn or soybean planting (Table 2). Cover crop was sown in 0.18-m rows, while corn and soybean were sown in 0.76-m rows. The main crops of corn and soybean were irrigated at the Harvard site from July to August. Note that the winter rye CC was never irrigated. The current study is part of a larger study described in detail by Barker et al. (2018), Koehler-Cole et al. (2020), Ruis et al. (2020), and Koehler-Cole et al. (2023). Cover crop biomass was collected annually in spring at termination by placing two 0.3 × 1.5 m frames aligned with the main crop rows. All CC biomass within the frame was clipped at the soil surface and dried at 60˚C in a forced-air oven for 3 days to reach constant weight.

2.2 | Soil physical properties

A number of compaction, structural, and hydraulic properties were determined. Soil physical properties, including cone index (compaction indicator) and water infiltration were determined in the field, while other properties, including soil bulk density, wet-aggregate stability, and water retention, were determined in the laboratory. Cone index was measured as soil penetration resistance using a cone penetrometer (Eijkelkamp Co.; Lowery & Morrison, 2002) at five locations per plot for depths of 0–5, 5–10, 10–20, and 20–30 cm. The penetration resistance values were then converted to cone index using the cone area. It is not uncommon for cone index to be correlated with gravimetric water content. However, in our study, no correlation existed for either site at any depth interval (data not shown), thus we did not use corrective equations (Blanco-Canqui et al., 2005; Busscher et al., 1997). Cumulative water infiltration and water infiltration rates were determined using a double ring infiltrometer by measuring water height (Reynolds et al., 2002). The double rings were 75-cm diameter for the outer ring and 25 cm for the inner ring. The rings were installed in non-trafficked areas. Water infiltration was measured at times of 0, 1, 2, 3, 4, 5, 10, 30, 60, 90, 120, 150, and 180 min and then water infiltration rate and cumulative water infiltration were computed (Reynolds et al., 2002).

At the time of field measurements, we collected 5-cm diameter × 5-cm high intact soil cores using a hammer-driven sampler and soil samples using a hand probe. The intact soil cores were collected from 0 to 5 and 5 to 10 cm depths at two locations per plot. The intact soil cores were sealed in plastic bags and stored at 4˚C until analysis. The soil samples with the hand probe were collected from 0 to 5, 5 to 10, 10 to 20, and 20 to 30 cm depths with a 1.75-cm diameter probe from 10 locations per plot. The hand probe samples were dried at 60˚C in a forced-air oven for 3 days, weighed, and stored for further analysis.

To determine bulk density and water retention, we used the intact soil cores. The intact soil cores were trimmed flush with the metal core and cheesecloth secured with a rubber band at the bottom of the core to prevent soil loss. The trimmed cores were slowly saturated with tap water from the bottom up for 3 days. Water retention was then determined at −33 kPa (field capacity) and −1500 kPa (permanent wilting point) matric potentials using low- and high-suction pressure extractors. Water retention at low suction (−33 kPa matric potential) was determined by placing the saturated soil cores in the low suction extractor and applying −33 kPa pressure. After equilibrium was achieved, the cores were weighed and a subsample collected, weighed, dried at 105˚C, and reweighed to determine gravimetric water content at −33 kPa. The remaining soil was air-dried, ground, and passed through a 2-mm sieve. The 2-mm sieved soil was packed in 1 cm × 5 cm rings on −1500 kPa ceramic plates, allowed to saturate for 24 h, placed in a high-pressure extractor, and −1500 kPa pressure was applied (Dane & Hopmans, 2002). After equilibrium was reached at −1500 kPa matric potential, the soil in the rings was dried at 105 ˚C for 24 h to determine water content. Soil bulk density was determined from the intact soil cores using the core method (Blake & Hartge, 1986). Bulk density was then used to compute volumetric water content at −33 and −1500 kPa matric potentials. The difference in volumetric water content between −33 and −1500 kPa was considered plant available water (Dane & Hopmans, 2002).

The hand probe samples were used to determine bulk density for depths below 10 cm using the core method (Blake & Hartge, 1986). Soil wet-aggregate stability was determined using the wet sieving method (Nimmo & Perkins, 2002). A portion of the air-dry samples collected with the hand probe was sieved through 8 mm. About 50 g of the sieved soil was weighed for the analysis of wet aggregate stability. The soil was placed on a stack of nested sieves with openings of 4.75, 2.00, 1.00, 0.50, and 0.25 mm. The 4.75-mm sieve contained filter paper to assist with rewetting of the aggregates through capillary action for 10 min. The filter paper was then removed and samples sieved mechanically for 10 min. The aggregates

TABLE 1 Monthly and long-term (1969–2022) mean temperatures and precipitation for the rainfed and irrigated experimental sites in Nebraska.

	Temperature (˚C)										Precipitation (mm)									
	Rainfed site																			
Months	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**Long term**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**Long term**
January	−6.2	−3.4	−5.4	−3.4	−7.4	−4.9	−4.2	−2.9	−6.1	−5.8	2	2	21	19	19	7	24	19	7	13
February	−6.3	−6.9	0.3	2.6	−6.0	−9.8	−1.8	−10.2	−3.4	−3.4	12	32	14	11	17	25	1	13	2	14
March	1.4	5.2	7.2	5.1	3.6	−0.3	5.3	7.0	3.6	3.5	5	20	25	57	76	58	35	122	43	49
April	10.0	11.2	11.4	10.8	5.7	10.7	8.9	9.5	8.2	10.2	81	90	123	61	7	30	13	50	30	54
May	16.3	15.2	15.4	15.6	19.8	14.1	14.4	15.5	16.0	16.2	162	195	185	197	75	171	73	108	109	142
June	21.7	21.5	24.2	22.8	23.7	21.2	24.1	23.2	22.4	22.1	208	151	102	53	156	113	56	100	76	115
July	21.5	23.2	23.7	24.7	22.8	24.6	24.6	23.6	24.8	24.2	14	89	94	82	90	67	61	71	26	66
August	22.8	21.3	22.6	20.8	22.3	21.8	23.1	23.3	23.6	22.9	174	192	141	111	82	80	43	182	73	120
September	17.4	20.9	19.9	19.5	19.4	21.2	17.4	19.9	19.7	18.4	78	100	74	126	192	110	48	40	27	88
October	12.6	12.8	13.3	12.2	9.2	8.4	8.4	12.9	11.4	11.2	83	13	39	109	61	111	17	132	16	64
November	0.1	6.4	7.6	3.4	−0.2	1.8	6.1	5.6	4.4	3.4	6	42	22	5	20	22	27	11	12	18
December	−1.3	0.1	−4.2	−2.5	−1.8	−0.7	−1.8	1.3	−5.5	−3.2	38	131	57	6	61	41	24	7	27	44
Annual average	9.7	10.6	11.3	10.9	9.3	9.0	10.4	10.7	9.8	9.9										
Annual sum											861	1057	893	855	855	832	420	854	445	786
	Irrigated site																			
January	−3.4	−1.6	−2.9	−2.5	−4.6	−2.6	−2.5	−0.9	−3.7	−2.6	9	6	17	38	9	8	22	33	8	17
February	−4.4	−4.1	1.9	3.4	−4.5	−6.9	−0.4	−9.6	−2.6	−3.1	8	26	31	8	15	23	1	15	0	14
March	2.3	6.6	7.8	5.9	4.3	0.9	6.2	7.3	4.2	5.1	2	7	8	30	28	67	37	160	35	42
April	10.7	11.7	11.6	11.2	5.7	11.2	9.1	9.8	9.5	10.1	54	54	105	76	27	11	13	41	47	48
May	16.9	15.6	15.9	16.1	19.7	14.2	14.9	15.9	16.1	16.2	58	97	135	198	73	238	98	143	150	132
June	22.4	22.6	24.8	23.7	24.5	21.5	8.1	23.6	23	23.4	191	213	11	40	143	122	43	58	81	100
July	22.5	7.7	24.6	25.6	23.8	24.9	24.8	23.9	24.8	24.4	44	148	65	51	132	79	97	57	140	90
August	23.3	22.5	23.4	21.3	22.7	22.6	23.2	24.2	23.4	22.9	222	47	55	90	111	217	61	53	18	97
September	18.1	22.1	19.8	19.8	19.6	21.9	17.6	20.8	20.3	20.0	51	39	89	61	135	41	30	47	46	60
October	13.2	13.9	14.3	12.4	9.6	8.6	9.4	13.1	12.1	11.8	25	29	46	111	113	48	6	68	15	51
November	1.6	7.1	8.2	4.9	1.6	2.7	7.3	6.3	2.7	4.7	3	54	30	4	19	30	41	10	9	22
December	−0.89	0.7	−2.7	−1.3	−0.6	0.3	−0.1	2.3	−4.4	−0.7	14	64	24	7	111	41	16	7	14	33
Annual Average	10.2	11.8	12.2	11.7	10.2	9.9	5.7	11.4	10.4	9.8										
Annual Sum											680	783	614	712	915	924	465	691	562	705

TABLE 2 Cover crop planting and termination dates for the 8-year experiments in rainfed and irrigated sites in Nebraska.

Cover crop management	Rainfed site	Irrigated site
Cover crop planting dates	October 23, 2014	October 21, 2014
	October 14, 2015	October 12, 2015
	October 26, 2016	October 21,2016
	November 22, 2017	late October 2017
	September 20,2018	October 29, 2018
	September 11, 2019	October 28, 2019
	September 8, 2020	November 6, 2020
	Early September 2021	Early November 2021
Cover crop termination dates	May 2, 2015	April 29, 2015
	April 22, 2016	April 22, 2016
	May 9, 2017	May 5, 2017
	April 19, 2018	April 16, 2018
	5 May 5 2019	April 16, 2019
	May 1, 2020	May 19, 2020
	May 1, 2021	May 10, 2021
	Early May 2022	Mid-May 2022

from each sieve were dried at 105˚C for 2 days, weighed, and used to compute wet aggregate stability as mean weight diameter of water-stable aggregates (MWD; Nimmo & Perkins, 2002).

2.3 | Soil chemical properties

We determined soil chemical properties of soil pH, electrical conductivity (EC), cation exchange capacity, and concentrations of NO_3^-, total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) on air-dry soil samples. We also determined soil organic C and particulate organic matter (POM) concentrations. Soil pH was determined using a 1:1 soil:water slurry and pH electrode while EC was determined using a saturated paste method (Peters et al., 2015; Whitney et al., 2015). Nitrate-N concentration was determined using the cadmium (Cd) reduction technique (Gelderman & Beegle, 2015). Soil P concentration was determined using Bray extract and colorimetric techniques (Frank et al., 2015). The concentrations of K, Ca, and Mg were determined from Mehlich III soil extracts with atomic absorption spectroscopy (Warncke & Brown, 2015). The cation exchange capacity was the sum of K, Ca, Mg, and Na cations.

Particulate organic matter was determined by loss-on-ignition using the methods of Cambardella et al. (2001). About 30 g of 2 mm sieved air-dried soil samples were dispersed in 5 g L^{-1} sodium hexametaphosphate solution for 24 h by reciprocal shaking. The dispersed sample was passed through 0.5-mm and 53-µm sieves. The portion of sample collected on the 0.5-mm sieve was the coarse POM while the portion collected on the 53-µm sieve was the fine POM. Coarse and fine POM samples were dried at 60˚C, weighed, ignited at 450˚C in a muffle furnace for 4 h, and weighed again. Soil organic C concentration was determined on a fraction of the air-dry sample passed through 0.25-mm sieve using the dry combustion technique on a Flash 2000 CN analyzer (Thermo Fisher Scientific; Nelson & Sommers, 1996). Soil organic C stock for each depth was computed on an equivalent mass of soil to account for any differences in soil bulk density among treatments (Ellert et al., 2001).

2.4 | Soil biological properties

Soil biological properties were assessed as microbial biomass and community structure using phospholipid fatty acid analysis (PLFA). We sieved air-dried samples through 2 mm and analyzed the sieved samples by the methods of Hamel et al. (2006). The fatty acids were classified into the microbial groups as follows: 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 3 OH, 11:0 2OH, 11:03OH, 11:0 iso 3OH, 12:2 OH, 12:0 3OH, 13:0 iso 3OH, 14:0 2OH, 14:0 3 OH, 15:0 anteiso, 16:0 iso; 16:1 ω7c, 16:1 ω7t, 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.

2.5 | Statistical analysis

All statistical analysis was conducted using SAS 9.4 (SAS Institute, 2022). The distribution of the data was checked for normality with the Shapiro–Wilk test using the PROC UNIVARIATE analysis. Data were not transformed as they were normally distributed. Analysis of variance was performed on all soil properties by site and depth using PROC GLIMMIX in SAS for a randomized complete block design. The fixed factor was CC and random factor was replication. Treatment means were separated using least significant differences at the 0.05 probability level.

Relationships among soil properties, annual CC biomass production, and cumulative CC biomass production across the

TABLE 3 Winter rye cover crop biomass production for the 8-year experiments in rainfed and irrigated sites in Nebraska.

Year	Cover crop biomass production (Mg ha^{-1})	
	Rainfed site	Irrigated site
2015	0.65	1.10
2016	1.48	2.15
2017	0.92	2.63
2018	0.02	0.07
2019	0.05	1.03
2020	0.85	0.34
2021	0.21	0.29
2022	0.28	0.25
Mean ± SD	0.56 ± 0.51	0.98 ± 0.95

8 years by site were studied using Pearson correlation coefficients and their significance at the 0.05 probability level obtained by PROC CORR in SAS. As mentioned earlier, there were two cropping systems (corn–soybean and continuous corn) at the rainfed site and only one (corn–soybean) at the irrigated site. However, cropping system × CC interaction was not significant for any soil property at the rainfed site. Thus, data were averaged across both cropping systems for the analysis of CC impacts on soil properties.

3 | RESULTS

3.1 | Cover crop biomass production

Winter rye CC biomass production was relatively low and highly variable among the 8 years for each site (Table 3). At the rainfed site, CC biomass production ranged from 0.02 to 1.48 Mg ha^{-1} among years with an average of 0.56 ± 0.51 Mg ha^{-1} across the 8 years, while at the irrigated site, it ranged from 0.07 to 2.63 Mg ha^{-1} with an average of 0.98 ± 0.95 Mg ha^{-1}. As mentioned earlier, CCs were not irrigated in this study. The high variability in CC biomass production is mainly attributed to fluctuations in precipitation and temperature among years. A correlation of CC biomass production with mean annual precipitation and mean annual temperature was not significant ($r < 0.01$; $p > 0.10$). However, the correlation of CC biomass production with mean monthly precipitation and mean monthly temperature during the month of April, a period of most active CC growth, was significantly correlated with CC biomass production (Figure 1a,b). Differences in precipitation input during April among years explained 53% of the variability in CC biomass production at the rainfed site (Figure 1a) and 56% of the variability at the irrigated site (Figure 1b). Differences in temperature among years for the same month (April) explained 34% (significant only at $p = 0.12$) of the variability at the rainfed site (Figure 1c) in CC biomass production and 47% of the variability at the irrigated site (Figure 1d).

3.2 | Soil physical properties

Cover crop impacts on soil compaction parameters of cone index and bulk density differed by site and soil depth (Figure 2a–d). At the rainfed site, CC altered neither cone index nor bulk density at any depth (Figure 2a,c). However, at the irrigated site, CC reduced cone index by 0.95 MPa in the 0–5 cm depth and by 0.55 MPa at the 5–10 cm, but not below 10 cm depth (Figure 2b). Also, at this site, CC reduced bulk density by 0.32 Mg m^{-3} in the 0–5 cm depth only (Figure 2d). Cover crop affected MWD at both sites, although the effects differed by depth (Figure 3a,b). At the rainfed site, CC increased MWD by 0.39 mm in the 0–5 cm depth and by 0.11 mm in the 10–20 cm depth but not at other depth intervals (Figure 3a). At the irrigated site, CC increased MWD by 0.79 mm in the 0–5 cm depth only (Figure 3b). Cover crop affected neither water infiltration rate (data not shown) nor cumulative water infiltration (Figure 4a,b) at any site. Also, CC had no effect on water retained at −0.33 kPa and −1500 kPa matric potentials and plant available water (Table 4).

3.3 | Chemical properties and soil carbon

Cover crop had minimal effects on soil fertility or chemical properties at both sites and all depths (Table 5). At both sites, CC increased coarse POM, fine POM, and total POM concentrations in the 0–5 cm depth only (Figure 5a–f). At the rainfed site, CC increased coarse POM by 0.9 mg g^{-1} (Figure 5a), fine POM by 1.9 mg g^{-1} (Figure 5b), and total POM by 2.8 mg g^{-1} (Figure 5c). At the irrigated site, CC increased coarse POM by 6.2 mg g^{-1} (Figure 5d), fine POM by 7.2 mg g^{-1} (Figure 5e), and total POM by 13.4 mg g^{-1} (Figure 5f). Cover crop affected soil organic carbon (SOC) concentration (Figure 6a,b) and SOC stocks (Figure 6c,d) differently at the two sites. At the rainfed site, CC increased SOC concentration by 2 g kg^{-1} (Figure 6a) and SOC stocks by 1 Mg ha^{-1} in the 0–5 cm depth only (Figure 6c). At the irrigated site, CC had no effect on SOC concentration (Figure 6b) or SOC stocks (Figure 6d).

3.4 | Soil microbial biomass and community structure

Similar to soil physical and chemical properties, CC effects on soil microbial biomass and community structure varied by site and soil depth. At the rainfed site, CC increased total

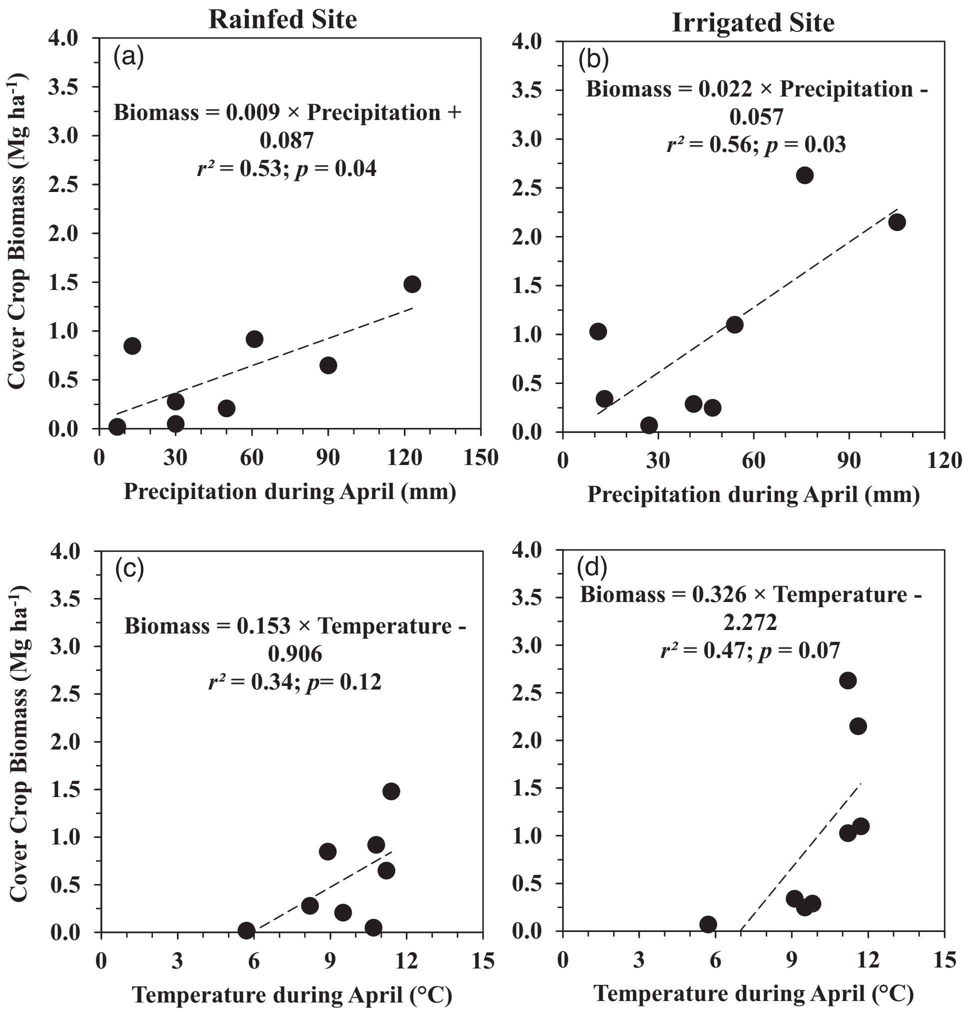

FIGURE 1 Correlations of cover crop biomass production with mean monthly precipitation (a and b) and mean annual temperature (c and d) during April across the 8 years in rainfed and irrigated sites in Nebraska.

TABLE 4 Impacts of winter rye cover crop (CC) on soil volumetric water content at field capacity (−33 kPa matric potential) and permanent wilting point (−1500 kPa matric potential) and plant available water at rainfed and irrigated sites in Nebraska.

Treatment	Soil depth (cm)	Water content at −33 kPa (cm^3 cm^{-3})	Water content at −1500 kPa (cm^3 cm^{-3})	Available water (cm^3 cm^{-3})
		Rainfed site		
No CC	0–5	0.28	0.14	0.15
CC		0.28	0.13	0.16
No CC	5–10	0.27	0.22	0.06
CC		0.26	0.22	0.03
		Irrigated site		
No CC	0–5	0.28	0.14	0.13
CC		0.30	0.12	0.18
No CC	5–10	0.28	0.22	0.07
CC		0.29	0.21	0.08

Note: There were no statistically significant differences between treatments at $p < 0.05$.

TABLE 5 Impacts of winter rye cover crop (CC) on soil fertility parameters at rainfed and irrigated sites in Nebraska.

Treatment	Soil depth (cm)	pH	EC ($dS\ m^{-1}$)	NO_3^- ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	P ($g\ kg^{-1}$)	K ($g\ kg^{-1}$)	Ca ($g\ kg^{-1}$)	Mg ($g\ kg^{-1}$)	Na ($g\ kg^{-1}$)	CEC ($cmol\ kg^{-1}$)
		Rainfed site									
No CC	0–5	5.7	0.30	34.7	2169	27.8	**455b**	1720	222	8.50	13.6
CC		5.7	0.36	58.3	2242	20.3	**535a**	1691	224	8.17	13.7
No CC	5–10	5.8	0.25	16.2	1831	17.2	357	1844	248	9.50	14.4
CC		5.9	0.28	18.2	1659	13.8	383	1834	228	8.67	14.3
No CC	10–20	5.8	0.19	11.1	1693	20.0	274	1912	259	9.83	14.7
CC		5.9	0.20	10.4	1555	15.2	285	1976	262	9.33	14.9
No CC	20–30	5.9	0.20	11.6	1726	16.2	216	1943	291	10.17	14.8
CC		6.0	0.21	7.78	1559	18.0	212	1933	281	11.83	15.1
		Irrigated site									
No CC	0–5	6.4	**0.15b**	16.7	**2192b**	67.0	384	1875	238	28.0	13.1
CC		6.6	**0.34a**	31.6	**2497a**	73.3	569	1945	260	21.7	13.8
No CC	5–10	6.7	0.14	9.80	1484	24.3	362	2336	306	38.0	15.3
CC		6.8	0.23	8.97	1571	17.0	298	2121	278	36.0	13.8
No CC	10–20	6.8	0.10	8.70	1307	13.0	319	2785	424	46.3	18.5
CC		6.7	0.26	4.67	1443	10.0	278	2435	376	42.7	16.2
No CC	20–30	7.0	0.19	12.1	1150	9.7	299	3163	554	144	21.8
CC		6.8	0.25	3.47	1329	7.0	291	2978	554	54.3	20.5

Note: Means with the same lowercase letter are not statistically significant at $p < 0.05$. Means with significant treatment effects are in bold.

Abbreviations: Ca, calcium; CEC, cation exchange capacity; EC, electrical conductivity; Mg, magnesium; N, nitrogen; P, phosphorus; K, potassium; Na, sodium.

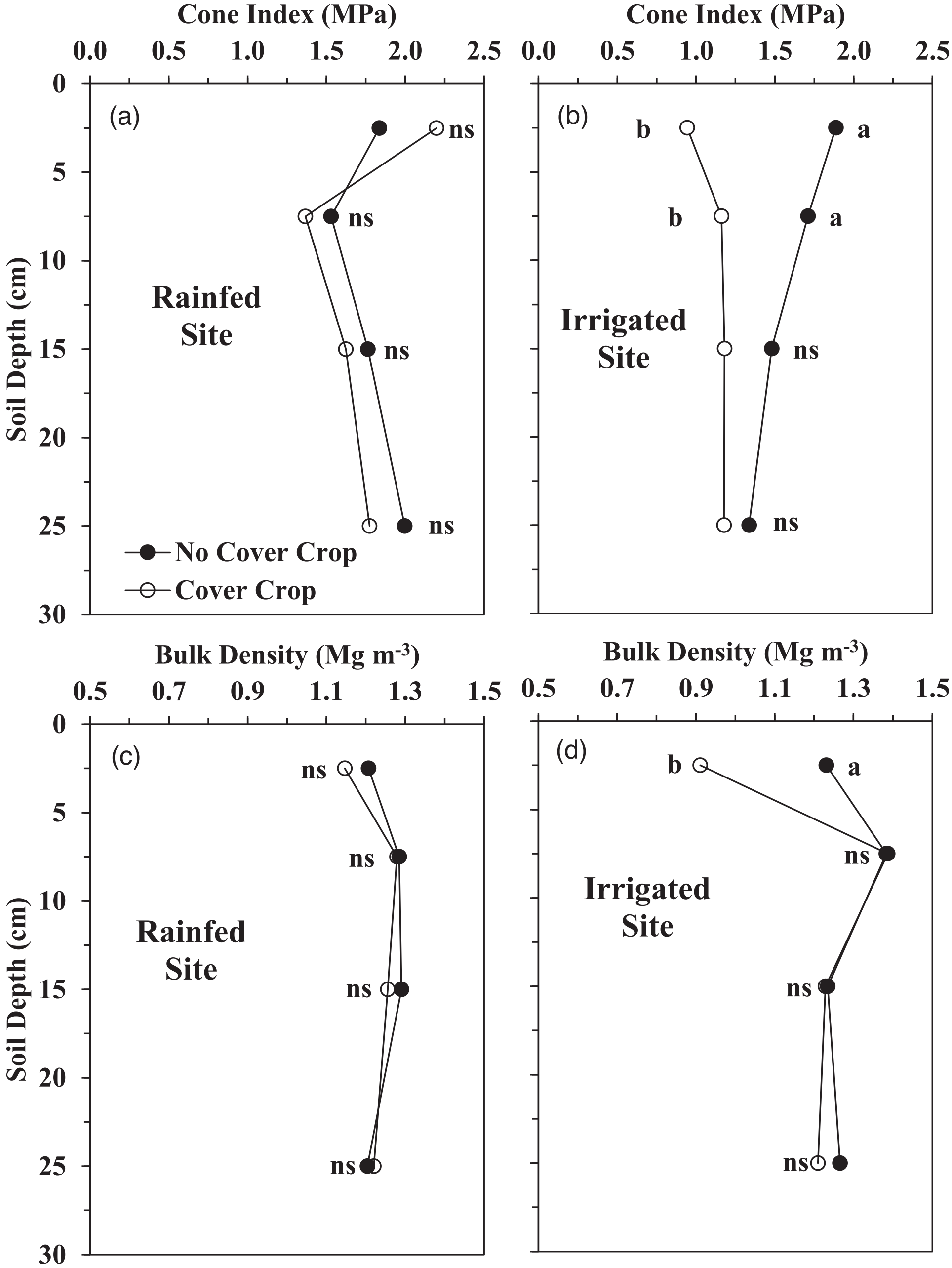

FIGURE 2 Impact of cover crop on cone index at a rainfed (a) and an irrigated (b) site and bulk density at a rainfed (c) and an irrigated site (d) after 8 years of cover crop management in Nebraska. Means with the same lowercase letter within a depth are not statistically significant at $p < 0.05$. ns denotes nonsignificant.

microbial biomass, gram negative bacteria, and total fungi at the 10–20 cm depth but not at other depths (Table 6). At the irrigated site, CC affected microbial biomass and community structure only in the upper 10 cm depth. It increased total microbial biomass by 3454 nmol g^{-1} in the 0–5 cm depth and by 924 nmol g^{-1} in the 5–10 cm depth relative to no CC. At the same site, CC increased gram negative bacteria by 734 nmol g^{-1}, total fungi by 431 nmol g^{-1}, and saprophytes by 348 nmol g^{-1} compared with no CC in the 0–5 cm depth. At the 5–10 cm depth, CC increased all microbial community components except actinomycetes. Cover crop increased total bacteria by 334 nmol g^{-1}, gram positive bacteria by 285 nmol g^{-1}, gram negative bacteria by 49 nmol g^{-1}, total fungi by 31 nmol g^{-1}, arbuscular mycorrhizal fungi by 4 nmol g^{-1}, and saprophytes by 27 nmol g^{-1}.

3.5 | Interrelationships among soil properties and cover crop biomass production

Relationships among soil properties and CC biomass production were few at both sites. At the rainfed site, total POM

TABLE 6 Impacts of winter rye cover crop (CC) on soil biological properties at rainfed and irrigated sites in Nebraska.

Treatment	Soil depth (cm)	Total microbial biomass (nmol g^{-1})	Total bacteria (nmol g^{-1})	Gram positive bacteria (nmol g^{-1})	Gram negative bacteria (nmol g^{-1})	Actinomycetes (nmol g^{-1})	Total fungi (nmol g^{-1})	Arbuscular mycorrhizal fungi (nmol g^{-1})	Saprophytes (nmol g^{-1})
		Rainfed site							
No CC	0–5	3584	1445	1113	332	400	245	64	181
CC		4599	1909	1274	534	488	432	97	335
No CC	5–10	2519	871	772	106	272	72	16	57
CC		2193	771	695	77	238	60	13	47
No CC	10–20	**1073b**	370	285	**85b**	113	**66b**	16	50
CC		**1306a**	452	344	**108a**	135	**81a**	21	60
No CC	20–30	1285	463	368	95	144	61	18	44
CC		1318	473	366	106	145	73	20	53
		Irrigated site							
No CC	0–5	**2131b**	776	638	**137b**	216	**90b**	30	**59b**
CC		**5585a**	2481	1610	**871a**	508	**521a**	115	**407a**
No CC	5–10	**1262b**	**407b**	**378b**	**29b**	124	**13b**	**1.69b**	**11b**
CC		**2186a**	**741a**	**663a**	**78a**	205	**44a**	**6.00a**	**38a**
No CC	10–20	1580	570	443	127	169	82	30	60
CC		1264	422	319	102	119	71	115	54
No CC	20–30	1377	481	384	87	146	58	22	43
CC		1318	479	391	88	151	59	17	45

Note: Means with the same lowercase letter are not statistically significant at $p < 0.05$ within a site and depth interval. Means with significant treatment effects are in bold.

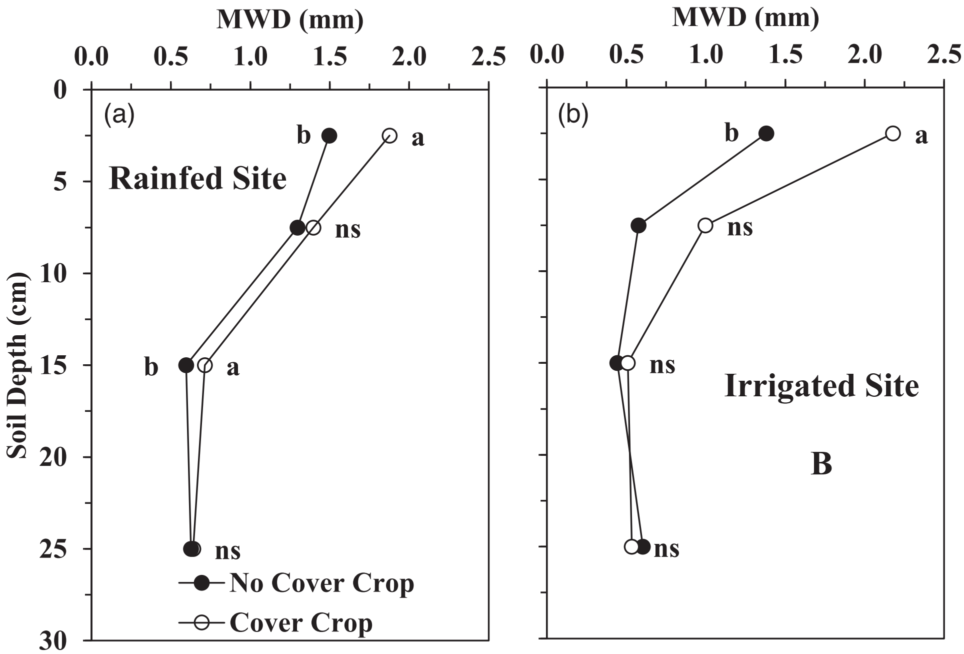

FIGURE 3 Impact of cover crop on mean weight diameter of water-stable aggregates (MWD) at a rainfed (a) and an irrigated (b) site after 8 years of cover crop management in Nebraska. Means with the same lowercase letter within a depth are not statistically significant at $p < 0.05$. ns denotes nonsignificant.

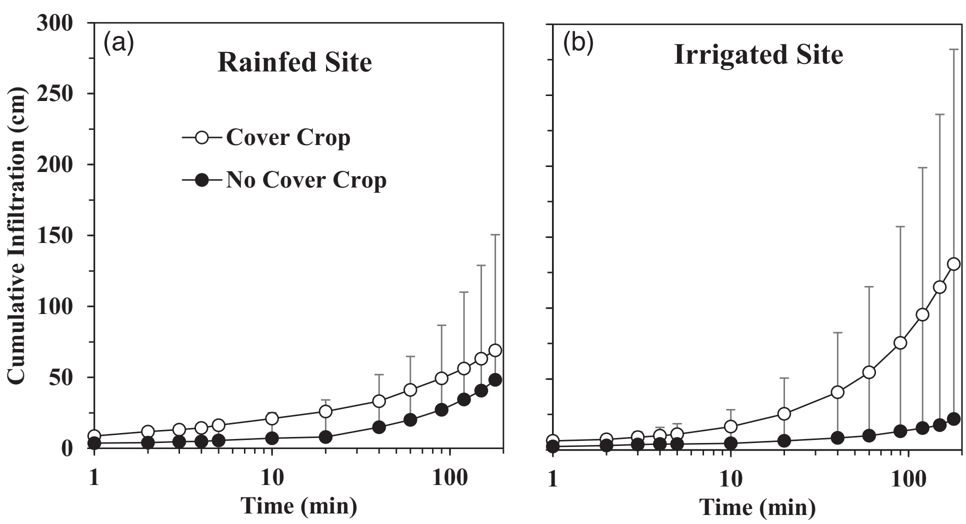

FIGURE 4 Impact of cover crop on cumulative water infiltration at a rainfed (a) and an irrigated site (b) after 8 years of cover crop management in Nebraska. Bars are the least significant differences (LSD) at each measurement time. There were no statistical differences among treatments at $p < 0.05$.

concentration was positively correlated with cumulative CC biomass production ($r = 0.70$, $p < 0.05$) and average annual CC biomass production ($r = 0.70$, $p < 0.05$). Cover crop biomass production explained 70% of the variability in total POM concentration. At the irrigated site, soil bulk density was negatively correlated with MWD ($r = -0.86$, $p < 0.05$), total POM ($r = -0.91$, $p < 0.05$), and microbial biomass ($r = -0.84$, $p < 0.05$). Cumulative and average annual CC biomass production were negatively correlated with soil bulk density ($r = -0.85$, $p < 0.05$) and cone index ($r = -0.95$, $p < 0.01$), but positively correlated with MWD ($r = 0.84$, $p < 0.05$). Cover crop biomass production explained 84%–95% of the variability in soil bulk density, cone index, and MWD.

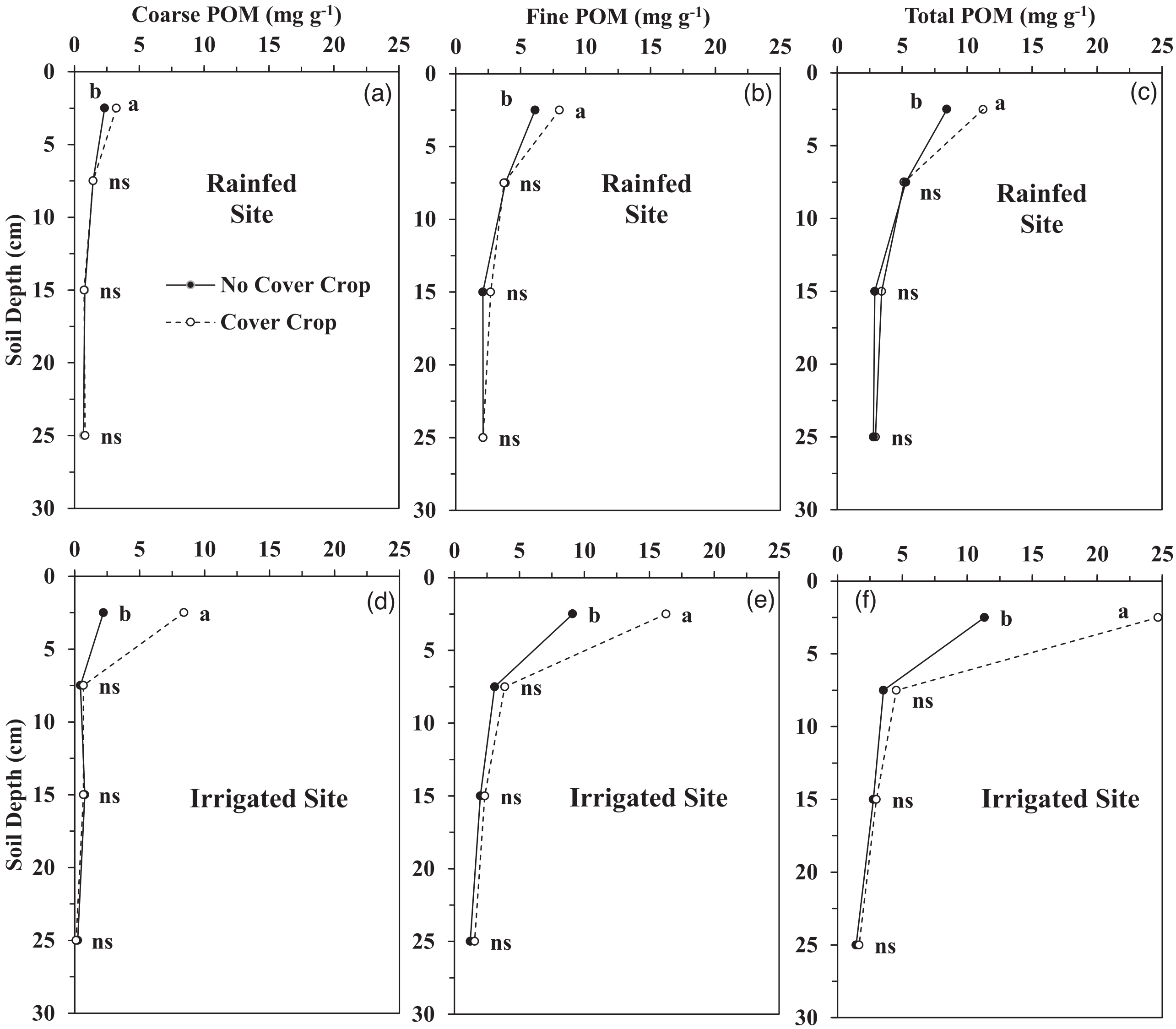

FIGURE 5 Impact of cover crop on coarse (a), fine (b), and total (c) particulate organic matter (POM) at a rainfed site and coarse (d), fine (e), and total (f) POM at an irrigated site after 8 years of cover crop management in Nebraska. Means with the same lowercase letter within a depth are not statistically significant at $p < 0.05$. ns denotes nonsignificant.

4 | DISCUSSION

Results from this study after 8 years of winter rye CC management in rainfed and irrigated no-till corn-based systems at two sites in the western US Corn Belt indicate that CC improves soil physical, chemical, and biological properties mainly in the shallow surface (0–5 cm) and rarely below. They also indicate that even in the long term (8 years), CCs do not appear to impart changes in soil properties at deeper depths under the conditions of this study. Other studies in temperate regions have also found CCs can improve soil properties mostly near the soil surface (Anderson et al., 2022; Rorick & Kladivko, 2017; Ruis et al., 2017; Sindelar et al., 2019). The significant near-surface changes in soil properties with CCs are beneficial for many soil processes (e.g., erosion control), but the concern is that such improvement may be short-lived without consistent high inputs of biomass. Soil properties in the upper few centimeters of the soil are also rather dynamic and prone to rapid changes due to soil disturbance during planting or other field operations, freeze-thaw cycles, wet-dry cycles, and others. Additionally, one tillage operation could erase the positive changes that have taken 8 years to achieve.

The two soil properties that consistently changed with CC adoption at both sites after 8 years were soil POM concentration (labile organic matter) and wet aggregate stability (MWD). These two properties are often considered as the most sensitive indicators of changes in soil health status after a management shift (Gyawali et al., 2022; Lazicki et al., 2021; Thapa et al., 2018). However, it is important to

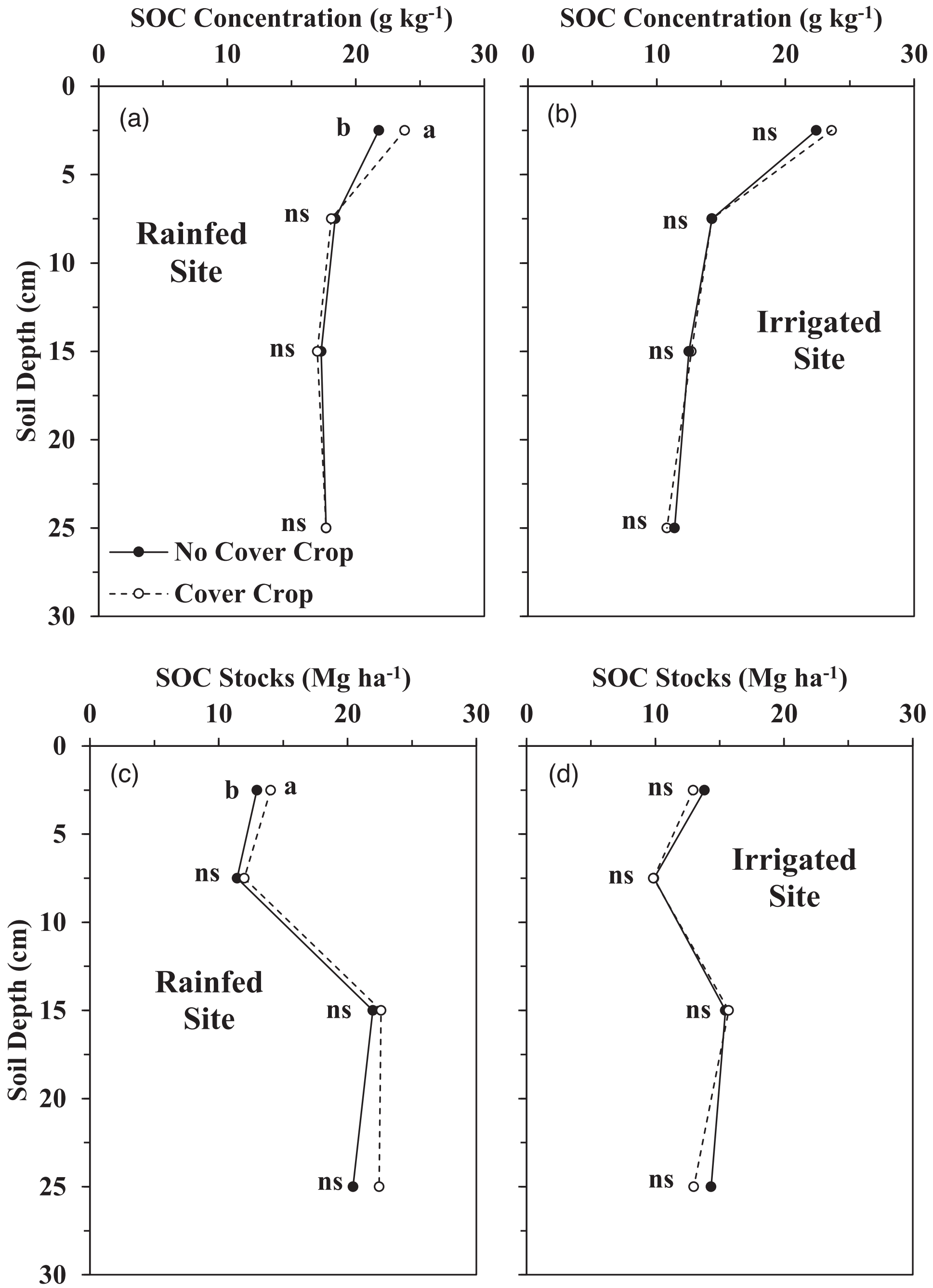

FIGURE 6 Impact of cover crop on soil organic carbon concentration at a rainfed (a) and an irrigated site (b), and soil organic carbon (SOC) stocks at a rainfed (c) and an irrigated (d) site after 8 years of cover crop management in Nebraska. Means with the same lowercase letter within a depth are not statistically significant at $p < 0.05$. ns denotes nonsignificant.

recognize that in this study, POM concentration and MWD did not rapidly change after CC adoption. Here, we compare our 8-year results with the results obtained in the fourth year reported by Ruis et al. (2020). After 4 years, winter rye CC did not significantly affect POM concentration and MWD (Ruis et al., 2020; Table 7); however, after 8 years, CC not only changed POM concentration and MWD but also other soil properties that had not significantly improved after 4 years (Table 7). Indeed, after 4 years, CC did not significantly affect any soil property at either site. This comparison strongly suggests that changes in soil properties after CC introduction can be slow in this environment, which is in accord with other studies in temperate regions (Anderson et al., 2022; McVay & Khan, 2022; Restovich et al., 2019; Rorick & Kladivko, 2017). Our results corroborate the need to monitor changes in soil properties across multiple years to gain a better understanding of the length of time it takes for CCs to improve soil properties and thus soil health.

TABLE 7 Impacts of a winter rye cover crop on select soil health indicators after 4 and 8 years compared with no cover crop in rainfed and irrigated sites in Nebraska.

	Rainfed site		Irrigated site	
Soil property	**4-Year effect**	**8-Year effect**	**4-Year effect**	**8-Year effect**
Bulk density	ns	ns	ns	Decrease
Cone index	ns	ns	ns	Decrease
Water infiltration	ns	ns	ns	ns
Mean weight diameter of water-stable aggregates	ns	Increase	ns	Increase
Particulate organic matter	ns	Increase	ns	Increase
Soil organic carbon	ns	Increase	ns	ns

Abbreviation: ns, not significant.

One of the main reasons for the relatively slow response of soil properties to CCs in typical corn-soybean systems in temperate regions can be the level of CC biomass produced. In these systems, CCs are often planted late in fall and terminated early in the spring of the following year, which limits CC biomass accumulation (Table 2). In our study sites, annual CC biomass production across the 8 years was highly variable and often lower than the 1 Mg ha^{-1} year^{-1} needed to reduce erosion (Table 3; Koehler-Cole et al., 2020). In addition, the rye CC biomass often had C:N ratios <30:1, which likely led to rapid decomposition (Koehler-Cole et al., 2020). Cover crops might be able to change some dynamic soil properties in the region sooner if CCs consistently produce high amounts of biomass (>1 Mg ha^{-1}) and achieve higher C:N ratios as a result of older, more mature plant tissues. For instance, a study in the same region found that CCs improved POM concentration and MWD in the first 3 years when CCs, which were terminated late at corn planting, produced between 1.6 and 2.9 Mg ha^{-1} year^{-1} (Ruis et al., 2017). When CC biomass production is <1 Mg ha^{-1} such as in our study sites (Table 3), then longer durations (>4 years) of CC may be needed to exert significant changes in soil properties. Further, low and variable amounts of CC residue can rapidly decompose after CC termination with limited or short-lived effects on soil properties (Austin et al., 2017; Garcia-Gonzalez et al., 2016). Soil properties can be highly correlated with CC biomass production (Anderson et al., 2022; Blanco-Canqui et al., 2014; McVay & Khan, 2022; Moore et al., 2014; Restovich et al., 2019, 2020; Ruis et al., 2017). Indeed, in our study, POM and CC biomass production were positively correlated at both sites.

Another reason for the slow response of soil properties to CCs in this study can be the relatively high biomass production from the main crops (corn and soybean). Companion studies including these two ongoing experimental sites showed that, averaged across sites and years, grain yield was 13.56 Mg ha^{-1} for corn (Koehler-Cole et al., 2023) and 4.61 Mg ha^{-1} for soybean (Koehler-Cole et al., 2020) under these no-till corn-based systems. Assuming a harvest index of 0.554 for corn (Ruiz et al., 2023) and 0.38 for soybean (Krisnawati & Adie, 2015), the amount of aboveground biomass input at our study sites would be 10.92 Mg ha^{-1} for corn and 7.52 Mg ha^{-1} for soybean. However, the amount of biomass input from CCs, averaged across sites and years, was only 0.77 Mg ha^{-1}, which is only about 7% of corn and 10% of soybean biomass input. The low CC biomass input may have thus limited the CC potential to significantly change soil properties in these systems.

It is important to point out that CC increased labile organic matter (POM) at both sites after 8 years, but CC increased SOC concentration and stocks only at the rainfed site and not at the irrigated site. The consistent increase in POM concentration across both sites corroborates that this soil property can be more responsive to CCs than other soil properties similar to some of the previous studies (Moore et al., 2014; Restovich et al., 2019; Ruis et al., 2017). However, the increase in total SOC stocks at one site only after 8 years can be a concern. The potential of CCs to sequester C in the soil is receiving much attention (McClelland et al., 2021; Poeplau & Don, 2015). Some consider that simply planting CCs can quickly accumulate C in all soils. Our results suggest that such potential of CCs is highly site-specific, and support findings from a recent review indicating that CCs may or may not sequester C in temperate regions (Blanco-Canqui, 2022). Specifically, CCs may have limited potential to accumulate C when biomass production is low (<1 Mg ha^{-1}), time after CC adoption is short (<5 years), and the initial soil C concentration is high (>20 g kg^{-1} or 2%; Blanco-Canqui, 2022). Soils in this study had an initial soil C concentration of about 22 g kg^{-1}, which may explain the limited accumulation of soil C after 8 years of CC introduction in these soils. At the site where CC increased soil C stocks, the rate of increase in soil C was 0.125 Mg ha^{-1} year^{-1}. This rate mirrors the average soil C accumulation rate reported in the review of studies from temperate regions by Blanco-Canqui (2022).

The lack of increase in water infiltration and plant available water with CC after 8 years deserves discussion. Results suggest that CCs may not always rapidly improve soil hydraulic properties in agreement with some studies in temperate regions (Çerçioğlu et al., 2019; Sindelar et al., 2019). An improvement in soil hydraulic properties is important for managing soil water and capturing and storing precipitation. We hypothesize that CCs could improve soil hydraulic properties in the long term (>8 years) as reported by some authors (Blanco-Canqui et al., 2011; Steele et al., 2012). Soil hydraulic properties often respond more slowly to management change compared to other soil properties. Again, the minimal effects of CC on water infiltration and plant available water may be partly due to the relatively low CC biomass production and the high initial soil C concentration (>22 g kg^{-1}) in our study sites.

Based on the results from this study, developing or identifying CC management strategies for no-till corn-based systems to produce larger amounts of biomass than in our study sites is desirable. Terminating CCs at main crop planting (Ruis et al., 2017) or planting into green CC (Acharya et al., 2022), and interseeding (Koehler-Cole et al., 2020) may be options to allow the CC to grow for longer periods and achieve more annual biomass production. Lengthening the CC growing season may not only increase aboveground CC biomass production but also belowground CC biomass production at various soil depths. Increased CC root biomass and root length density within the soil profile could improve soil properties at deeper depths than the shallow improvement in soil properties observed in the present study.

5 | CONCLUSIONS

This study investigating the 8-year impacts of a winter rye CC on soil health indicators in corn-based systems under rainfed and irrigated conditions at two sites in the western US Corn Belt indicates that CCs can improve many soil physical, chemical, and biological properties but primarily near the soil surface. Because these changes primarily occurred at the soil surface, the effects may be ephemeral and easily erased by natural or human-induced disturbances. Particulate organic matter and wet aggregate stability were two soil properties that increased at both sites near the surface and are considered key metrics of soil health. When results were compared with those previously reported from both sites from the fourth year of the study, our results indicate that CCs significantly improved soil properties only after 8 years (this study) and not after 4 years. Thus, even those soil properties (e.g., POM, wet aggregate stability) considered to be sensitive measures of soil health may not rapidly change after CC adoption. The relatively low CC biomass production and high biomass input from the main crops in corn-based systems can be some of the reasons for the slow response of soil properties to CC in this study. Alternative and innovative CC management strategies may be needed for CCs to produce biomass sufficient to alter soil health indicators. Overall, winter rye CCs appear to enhance soil properties mostly near the soil surface under the conditions of this study in the long term, warranting the need to develop CC management strategies to enhance CC biomass input and thus soil health at deeper depths in the soil profile.

AUTHOR CONTRIBUTIONS

Humberto Blanco-Canqui: Conceptualization; data curation; funding acquisition; project administration; software; supervision; writing—original draft. **Sabrina J. Ruis**: Formal analysis; methodology; validation; visualization; writing—review and editing. **Katja Koehler-Cole**: Investigation; project administration; resources; supervision; writing—review and editing. **Roger W. Elmore**: Conceptualization; funding acquisition; investigation; project administration; supervision; writing—review and editing. **Charles A. Francis**: Conceptualization; funding acquisition; project administration; supervision; writing—review and editing. **Charles A. Shapiro**: Conceptualization; investigation; validation; writing—review and editing. **Christopher A. Proctor**: Investigation; project administration; writing—review and editing. **Richard B. Ferguson**: Conceptualization; funding acquisition; project administration; supervision; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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