Received: 3 June 2019 | Accepted: 3 January 2020 | Published online: 30 March 2020

DOI: 10.1002/agj2.20143

Agronomy Journal

ARTICLE

Agronomy, Soils, & Environmental Quality

Impacts of cover crop planting dates on soils after four years

Sabrina J. Ruis[1] | **Humberto Blanco-Canqui**[1] | **Roger W. Elmore**[1] | **Christopher Proctor**[1] | **Katja Koehler-Cole**[1] | **Richard B. Ferguson**[1] | **Charles A. Francis**[1] | **Charles A. Shapiro**[2*]

[1]Department of Agronomy and Horticulture, Univ. of Nebraska-Lincoln, Lincoln, NE 68583, USA

[2]Univ. of Nebraska-Haskell Agricultural Laboratory, Concord, NE 68728, USA

Correspondence
Sabrina J. Ruis, Department of Agronomy and Horticulture, Univ. of Nebraska-Lincoln, Lincoln, NE 68583, USA.
Email: sruis2@unl.edu

Funding information
Nebraska Corn Board and Nebraska Soybean Board

*Retired

Abstract

Impacts of cover crop (CC) mixes and early CC planting on soil properties, CC biomass production, and CC biomass C input are not well understood. We assessed CC planting date (pre- or post-harvest) and CC type (rye [*Secale cereale* L.], mix of winter pea [*Pisum sativum* L.], hairy vetch [*Vicia villosa* L.], rye, and radish [*Raphanus sativus* L.], or no CC) effects on soil physical properties, organic matter, and CC biomass C input under three no-till continuous corn (*Zea mays* L.) and corn-soybean (*Glycine max* L.) sites in the eastern Great Plains after 4 yr. Across sites and years, pre-harvest-planted CCs produced 0.81 ± 0.52 (mean ± SD), post-harvest-planted 0.59 ± 0.44, rye 0.83 ± 0.52, and mix 0.57 ± 0.42 Mg biomass ha^{-1}. Compared to no CC, pre- and post-harvest–planted CC effects varied by site. Pre-harvest–planted CCs increased wet-aggregate stability by 17% and particulate organic matter by 31% under continuous corn at one of three sites compared with post-harvest-planted CCs. Similarly, the CC mix had variable effects on cone index but reduced bulk density by 7% at one site under continuous corn and increased wet-aggregate stability by 21% at another site under corn–soybean. Planting date, but not CC type, effects were slightly more evident under continuous corn than corn–soybean. Across sites and years, pre-harvest-plant CC had 0.29 ± 0.38 Mg biomass C ha^{-1}, post-harvest-planted 0.22 ± 0.30, rye 0.33 ± 0.37, and the mix 0.16 ± 0.27. Low CC biomass (<1 Mg ha^{-1}) production may explain the limited CC effects. Overall, pre-harvest-planted CCs and CC mixes had minimal effects on soil properties in this region after 4 yr.

1 | INTRODUCTION

Cropping system intensification with CCs could lead to improved soil properties and ecosystem services from the estimated 34 million ha of corn and soybean planted annually in the United States (Blanco-Canqui & Francis, 2016; Blanco-Canqui et al., 2015; USDA-NASS, 2018). Corn and soybean crops are grown in both rainfed and irrigated cropping systems, particularly in the Great Plains. In Nebraska alone, an estimated 2.11 million ha of corn (of 3.7 million ha total) and 1.11 million ha of soybean (of 2.26 million ha total) are irrigated (USDA-NASS, 2018). Winter CC biomass production and subsequent effects on soils may differ due to many factors including cropping system, CC species, CC management, and others. (Barker et al., 2018; Irmak, Sharma, Mohammed, & Djaman, 2018; Ruis, Blanco-Canqui, Jasa, Ferguson, & Slater, 2017; Sharma, Irmak, & Padhi, 2018; Villamil, Bollero, Darmody, Simmons, & Bullock, 2006).

Abbreviations: CCs, cover crops.

Cover crop planting date is one critical factor that may influence CC effects on soil properties. Early CC planting may consist of drilling following a short-season crop, broadcast seeding, or aerially seeding. While data on winter CC biomass production under different planting dates are relatively common (Balkcom, Massey, Mosjidis, Price, & Enloe, 2011; Duiker, 2014; Hayden, Ngouajio, & Brainard, 2015; Lawson, Cogger, Bary, & Fortuna, 2015; Murrell et al., 2017) published data on CC planting date effects on soil properties are limited. For example, in Michigan, Hayden et al. (2015) found that planting hairy vetch (*Vicia villosa* L.)–rye CC mix in late August to early September increased biomass production by 54–65% compared to planting in mid-September. Similar increases in biomass production were observed by Lawson et al. (2015) and Duiker (2014). Early broadcast planting is not without challenges as increasing biomass production could require higher seeding rates due to seed landing in leaf whorls, loss to predation, and poor soil-seed contact which can reduce germination. One study of early-broadcast seeding of rye in Minnesota showed that precipitation within a week of seeding improved CC establishment (Wilson, Baker, & Allan, 2013). Pre-harvest drill-planted CCs, as opposed to post-harvest drill-planted CCs, often produce more biomass due to longer CC growing season (Duiker, 2014), as they can establish better before winter under corn and soybean systems. Pre-harvest planting of CCs combined with warm temperatures and relatively high precipitation in fall through spring, can improve CC biomass production compared to cold or dry fall and spring and little snowfall (Duiker et al., 2014). Previous studies assessing CC planting date effects mainly focused on agronomic factors, CC biomass production, or soil nitrate concentration and not specifically on soil properties (Curran et al., 2018; Hashemi, Farsad, Sadeghpour, Weis, & Herbert, 2013; Hayden et al., 2015; Liebman et al., 2018; Parr, Grossman, Reberg-Horton, Brinton, & Crozier, 2011). Thus, the effects of pre-harvest (broadcast seeding) and post-harvest drill-seeded CCs on soil properties have not been directly compared.

Mixes of CCs are often thought to have greater positive effects on soil properties than single CC species due to the species diversity. The diversity of CC species including warm and cool season species, grasses, legumes, brassicas, and others can fill different ecological niches and thus contribute to more efficient resource use (Smith, Atwood, & Warren, 2014). These niches may include N_2 fixation, differences in root or canopy structure, residue quality, and others (Smith et al., 2014). Due to the differences in CC functional groups within a mixture, the enhanced resource efficiency could lead to greater CC biomass production, which may then differently impact soil ecosystem services (Smith et al., 2014; Wortman, Francis, & Lindquist, 2012). Published studies comparing CC biomass production between single species and mixes found no differences in biomass production (Holman et al., 2018; Hunter et al., 2019; Murrell et al., 2017; Wortman et al., 2012), increased biomass production with mixes compared to some single species (Murrell et al., 2017; Smith et al., 2014), or decreased biomass production (Appelgate, Lenssen, Wiedenhoeft, & Kaspar, 2017; Finney, White, & Kaye, 2016; Hunter et al., 2019). Several studies evaluated CC mix biomass production and its effects on weed suppression and effects on main crop yields (Finney et al., 2016; Noland et al., 2018; Smith et al., 2014; Wortman et al., 2012), but those investigating the effects of CC mixes on soil properties are fewer.

Core Ideas

- Pre- and post-harvest-planted mix and rye cover crops (CCs) had few effects on soils.
- Pre- and post-harvest-planted mix and rye CCs had similar effects on soils.
- Low CC biomass yield (<1 Mg ha^{-1}) for the 4 yr may have limited CC effects.

We reviewed studies (Table 1) in temperate regions that investigated effects of CC mixes on soil properties. In our review, the duration of studies with directly measured soil properties ranged from 2 to 17 yr. Cover crop mixes increased soil organic C content in three out of seven studies compared to no CC, and in two out of six studies that compared to single CC species. Two of three studies showed no changes in total N concentration with mixes compared to control or single species. The review generally showed no CC mix effect on bulk density, cone index, and wet-aggregate stability (Table 1). One study in Nebraska reported CC mixes reduced water infiltration by 64% compared to no CC (Table 1). In summary, the review indicates that CC mixes may or may not improve soil properties over single CC species.

Additional studies assessing effects of CC planting dates, CC types (mixes and single species), and their interactions on soil properties are needed. This information would allow farmers and researchers to better manage CCs under different cropping systems. Thus, our objective was to assess the influence of CC planting date (pre- or post-harvest) and CC type (no CC, cereal rye, or mix) on soil properties after 4 yr, including wet-aggregate stability, particulate organic matter, soil organic C, total N, sorptivity, compaction, and CC biomass C under continuous corn and corn–soybean rotations at three sites in the eastern Great Plains. Our hypotheses were that CC planting date would improve soil properties in this order: pre-harvest > post-harvest > no CC and CC type in this order: mixes > rye > no CC due to the increased biomass production with pre-harvest planting and potential for greater biomass production and increased species diversity with mixes.

TABLE 1 Cover crop (CC) mix and single species effects on soil properties across different climates, study durations, and cropping systems. NT = no-till; I = irrigated; AWP = Austrian winter pea. No values after the CC species indicates CC biomass production was not reported

Location	Precipitation mm	Temperature °C	Soil	Duration yr	Tillage	Cropping system	Depth cm	Key finding	Reference
Single species vs. CC Mix									
Soil organic C									
Texas	486	16.0	Sandy loam	17	NT	Cotton (I)	0–15	Mix (rye–hairy vetch–radish–winter pea with 3.6 Mg ha^{-1} biomass production) did not differ from single species (rye with 4.4 Mg ha^{-1} biomass production)	Lewis et al., 2018
Ohio	917	10.0	Silt loam	>3	NT	Corn–soybean–wheat–CC	0–10	Mix (radish–AWP) increased C by 22% over radish but did not differ from AWP	Stavi et al., 2012
Total N									
Ohio	917	10.0	Silt loam	>3	NT	Corn–soybean–wheat–CC	0–10	Mix (radish-AWP) increased total N by 96% compared to radish and 74% compared to AWP	Stavi et al., 2012
Bulk density									
Texas	61	16.0	Sandy loam	17	NT	Cotton (I)	0–15	Mix (rye–hairy vetch–radish–winter pea with 3.6 Mg ha^{-1} biomass production) did not differ from single species (rye with 4.4 Mg ha^{-1} biomass production)	Lewis et al., 2018
Ohio	917	10.0	Silt loam	>3	NT	Corn–soybean–wheat–CC	0–10	Mix (radish–AWP) did not differ from AWP, but reduced bulk density by 11% relative to radish	Stavi et al., 2012
Aggregate stability									
Ohio	917	10.0	Silt loam	>3	NT	Corn–Soybean–Wheat–CC	0–10	Mix (radish–AWP) did not differ from radish, but mixes reduced aggregate stability by 26% compared to AWP	Stavi et al., 2012
CC Mix vs. No CC									
Soil organic C									
Nebraska	743	10.2	Silt loam	13	NT	Seed corn–soybean (I)	0–5	Mixes (variable species) increased C by 35% over no CC	Sharma et al., 2018
New York	919	9.1	Silt loam	4	NT	Corn	0–15	Mix (annual ryegrass–red clover–crimson clover–hairy vetch) did not differ from no CC	Nunes et al., 2018
Total N									
Nebraska	743	10.2	Silt loam	13	NT	Seed corn–soybean (I)	0–5	Mix (variable species) did not differ from no CC	Sharma et al., 2018

(Continues)

TABLE 1 (Continued)

Location	Precipitation mm	Temperature °C	Soil	Duration yr	Tillage	Cropping system	Depth cm	Key finding	Reference
Cone index									
New York	919	9.1	Silt loam	4	NT	Corn	0–15	Mix (annual ryegrass–red clover–crimson clover–hairy vetch) did not differ from no CC	Nunes et al., 2018
Aggregate stability									
New York	919	9.1	Silt loam	4	NT	Corn	0–15	Mix (annual ryegrass–red clover–crimson clover–hairy vetch) did not differ from no CC	Nunes et al., 2018
Water infiltration									
Nebraska	599	na	Silt loam	14	NT	Corn-soybean (I)	na	Cover crops reduced water infiltration by 64%	Irmak et al., 2018
CC Mix vs. single species vs. No CC									
Soil organic C									
Massachusetts	1168	8.75	Sandy loam	9	Tilled	Corn	0–25	Mix increased C by 32% over no CC, but rye was similar to both no CC and mix	Ding et al., 2006
Iowa	834	9.2	Loam to clay loam	6	NT	Corn–soybean	0–5	Mix (oat–rye with 2.3 Mg ha^{-1} biomass production) and single species (oat with 0.6 Mg ha^{-1} and rye with 2.1 Mg ha^{-1} biomass production did not differ from no CC	Kaspar et al., 2006
Argentina	1019	17.5	Silt loam	5	NT	Soybean	0–5	Mix (oat–vetch with 2.7 Mg ha^{-1} biomass production) increased C by 26% over no CC, and 0 to 9% over single species (wheat or oat with 3.3 Mg ha^{-1} and vetch with 1.8 Mg ha^{-1} biomass production)	Duval et al., 2016
Illinois	1045	10.9	Silty clay loam	2	Tilled	Soybean	0–50	Mix (radish with hairy vetch, rye, triticale, or buckwheat) and radish did not differ from no CC	Acuna & Villamil, 2014
Tennessee	1361	14.9	Silt loam	3	NT	Corn–soybean	0–15	Mixes (rye–crimson clover, rye–hairy vetch, rye–oat–turnip–radish–crimson clover) and single species (rye or wheat) did not differ from no CC	Chu et al., 2017
Coarse particulate organic matter									
Argentina	1019	17.5	Silt loam	5	NT	Soybean	0–5	Mix (oat–vetch with 2.7 Mg ha^{-1} biomass production) increased cPOM over no CC by 89% and mixes increased by 0–32% over single species (wheat or oat with 3.3 Mg ha^{-1} and vetch with 1.8 Mg ha^{-1} biomass production)	Duval et al., 2016

(Continues)

TABLE 1 (Continued)

Location	Precipitation mm	Temperature °C	Soil	Duration yr	Tillage	Cropping system	Depth cm	Key finding	Reference
Fine particulate organic matter									
Argentina	1019	17.5	Silt loam	5	NT	Soybean	0–5	Mix (oat–vetch with 2.7 Mg ha^{-1} biomass production) did not differ from single species (wheat or oat with 3.3 Mg ha^{-1} and vetch with 1.8 Mg ha^{-1} biomass production), but both mix and single species increased fPOM by 22% over no CC	Duval et al., 2016
Total N									
Illinois	1045	10.9	Silty clay loam	2	Tilled	Soybean	0–50	Mix (radish with hairy vetch, rye, triticale, or buckwheat) and radish did not differ from no CC	Acuna & Villamil, 2014
Bulk density									
Iowa	834	9.2	Loam to clay loam	6	NT	Corn–soybean	0–5	Mix (oat–rye with 2.3 Mg ha^{-1} biomass production) and single species (oat with 0.6 Mg ha^{-1} and rye with 2.1 Mg ha^{-1} biomass production did not differ from no CC	Kaspar et al., 2006
Illinois	1045	10.9	Silty clay loam	2	Tilled	Soybean	0–10	Mixes (radish with hairy vetch, rye, triticale, or buckwheat) and single species (radish) did not differ from no CC	Acuna & Villamil, 2014
Cone index									
Illinois	1045	10.9	Silty clay loam	2	Tilled	Soybean	0–10	Mixes (radish with hairy vetch, rye, triticale, or buckwheat) and single species (radish) did not differ from no CC	Acuna & Villamil, 2014
Aggregate stability									
Illinois	1045	10.9	Silty clay loam	2	Tilled	Soybean	0–10	Mixes (radish with hairy vetch, rye, triticale, or buckwheat) and single species (radish) did not differ from no CC	Acuna & Villamil, 2014

TABLE 2 Site descriptions and management of cover crop (CC) planting date and type experiment at three sites in Nebraska

	Site location		
	Haskell Agricultural Laboratory (Concord, NE)	**Eastern Nebraska Research and Extension Center (Mead, NE)**	**South Central Agricultural Laboratory (Harvard, NE)**
Site designation	1	2	3
Soil series	Coleridge: fine-silty, mixed, superactive, mesic Cumulic Haplustolls; Kennebec: fine-silty, mixed, superactive, mesic Cumulic Hapludolls, Baltic: fine, smectitic, calcareous, mesic Cumulic Vertic Endoquolls	Tomek: fine smectitic, mesic Pachic Argiudolls; Filbert: fine, smectitic, mesic Vertic, Argiabolls	Hastings: fine, smectitic, mesic Udic Argiustolls
Pre-harvest-planting into corn	18 Sept. 2014	8 Sept. 2014	18 Sept. 2014
	10 Sept. 2015	3 Sept. 2015	3 Sept. 2015
	8 Sept. 2016	6 Sept. 2016	30 Aug. 2016
	8 Sept. 2017	11 Sept. 2017	4 Sept. 2017
Pre-harvest planting into soybean	10 Sept. 2014	8 Sept. 2014	9 and 16 Sept. 2014
	10 Sept. 2015	9 Sept. 2015	3 Sept. 2015
	8 Sept. 2016	6 Sept. 2016	30 Aug. 2016
	8 Sept. 2017	20 Sept. 2017	4 Sept. 2017
Post-harvest planting into corn	28 Oct. 2014	23 Oct. 2014	21 Oct. 2014
	15 Oct. 2015	14 Oct. 2015	12 Oct. 2015
	11 Nov. 2016	11 Nov. 2016	14 Oct. 2016
	8 Nov. 2017	22 Nov. 2017	late Oct. 2017
Post-harvest planting into soybean	28 Oct. 2014	23 Oct. 2014	21 Oct. 2014
	15 Oct. 2015	14 Oct. 2015	12 Oct. 2015
	11 Nov. 2016	26 Oct. 2016	21 Oct. 2016
	8 Nov. 2017	22 Nov. 2017	late Oct. 2017
Termination (before corn)	17 Apr. 2015	16 Apr. 2015	15 Apr. 2015
	23 Apr. 2016	22 Apr. 2016	22 Apr. 2016
	9 May 2017	25 Apr. 2017	25 Apr. 2017
	27 Apr. 2018	19 Apr. 2018	16 Apr. 2018
Termination (before soybean)	28 Apr. 2015	2 May 2015	29 Apr. 2015
	22 Apr. 2016	5 May 2016	26 Apr. 2016
	5 May 2017	9 May 2017	5 May 2017
	24 Apr. 2018	16 May 2018	4 May 2018
Corn and soybean planting	1.5–3 wk after CC termination	2–3 wk after CC termination	1–4 wk after CC termination

2 | MATERIALS AND METHODS

2.1 | Site descriptions and experimental design

We conducted this study on three CC experiments located in south central and eastern Nebraska after 4 yr of treatment (Table 2). Table 2 shows the location, site designation of each site (1, 2, and 3), soil series description, and management. Soil texture ranged from silt loam to silty clay loam. Table 3 shows detailed weather data by month from September to May (CC growing period) for each site. The 4-yr mean precipitation was similar among the three study sites (Table 3). The 30-yr mean

TABLE 3 Average temperature and precipitation for each site by month and year, the 4-yr mean, the cumulative rainfall during the 9-mo cover crop period, and 30-yr means

	Average temperature			Average precipitation		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Month, Year	°C			mm		
2014–2015						
Sept.	16.6	17.7	17.2	71	87	48
Oct.	11.1	12.1	12.2	28	38	27
Nov.	–1.7	0.1	0.8	9	4	1
Dec.	–3.4	–1.1	–1.5	33	36	8
Jan.	–4.8	–3.2	–2.4	4	21	5
Feb.	–7.6	–7.0	–5.0	1	0	1
Mar.	4.9	5.4	6.1	15	19	5
Apr.	10.6	11.5	11.0	53	80	62
May	14.5	15.6	14.9	69	161	145
2015–2016						
Sept.	19.0	20.5	21.2	203	101	38
Oct.	11.8	13.2	13.2	19	10	37
Nov.	4.2	6.5	5.7	49	54	12
Dec.	–2.6	0.1	–0.3	32	120	50
Jan.	–7.1	–4.6	–3.1	22	18	7
Feb.	–2.0	0.3	1.1	46	13	23
Mar.	4.7	7.5	7.2	67	23	0
Apr.	9.3	11.9	11.0	156	129	138
May	15.2	16.2	15.4	94	154	172
2016–2017						
Sept.	18.4	19.9	19.2	58	61	67
Oct.	11.8	13.2	13.6	50	39	6
Nov.	6.2	7.2	6.9	36	19	30
Dec.	–5.9	–3.9	–3.8	27	53	18
Jan.	–5.6	–3.5	–3.3	20	14	27
Feb.	0.2	2.5	2.9	42	9	5
Mar.	3.2	5.5	5.5	27	55	22
Apr.	9.3	11.1	10.4	80	71	81
May	14.6	16.3	15.6	94	140	154
2017–2018						
Sept.	18.2	19.8	19.6	50	125	53
Oct.	10.4	12.0	11.3	88	114	102
Nov.	2.9	3.9	4.5	0	0	0
Dec.	–4.8	–3.4	–3.2	0	5	2
Jan.	–7.3	–5.5	–4.5	12	8	3
Feb.	–8.7	–5.5	–5.3	5	3	16
Mar.	1.6	3.9	4.1	27	48	11
Apr.	4.4	6.1	5.7	27	6	14
May	18.7	20.1	19.3	78	65	48
4-Yr mean						
Sept.	18.1	19.5	19.3	95	93	52
Oct.	11.3	12.6	12.6	46	50	43

(Continues)

TABLE 3 (Continued)

	Average temperature			Average precipitation		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Month, Year	°C			mm		
Nov.	2.9	4.4	4.5	23	19	11
Dec.	–4.1	–2.1	–2.2	23	53	20
Jan.	–6.2	–4.2	–3.3	15	15	11
Feb.	–4.5	–2.4	–1.6	24	6	11
Mar.	3.6	5.6	5.7	34	36	9
Apr.	8.4	10.2	9.5	79	71	74
May	15.7	17.1	16.3	84	130	130
9-Mo sum				423	475	360
30-Yr mean						
Sept.	16.3	18.2	18.1	73	77	63
Oct.	9.4	11.3	11.2	54	52	58
Nov.	0.4	3.4	3.7	42	39	34
Dec.	–5.7	–3.2	–2.4	21	24	30
Jan.	–7.3	–5.2	–4.4	20	15	8
Feb.	–4.4	–2.8	–1.8	20	16	16
Mar.	1.5	3.5	3.8	57	44	41
Apr.	8.1	10.2	9.9	82	72	66
May	14.7	16.1	15.7	113	111	135
9-Mo sum				482	449	450

precipitation from September to May ranged from 449 to 482 mm. We established the experiment at each site in fall 2014 using a factorial design arranged in a randomized complete block with four replications at sites 1 and 3, and three replications at site 2. The main crops were rainfed at sites 1 and 2 and sprinkler irrigated at site 3. However, CCs were not irrigated in any year.

This study on soil properties was conducted as part of a larger set of experiments that are described in detail by Barker et al. (2018). Treatments used in this study were pre-harvest- or post-harvest-seeding and CC treatments: no CC, cereal rye (300 seed m^{-2}) and four-way mix (188 seed m^{-2} in Years 1 and 2, 346 seed m^{-2} in Years 3 and 4). In Years 1 and 2, the four-way mix contained winter pea (*Pisum sativum* L.) (8 seeds m^{-2}), hairy vetch (*Vicia villosa* L.) (10 seed m^{-2}), cereal rye (150 seed m^{-2}), and radish (*Raphanus sativus* L.) (20 seed m^{-2}). In Years 3 and 4 the four-way mix contained winter pea (16 seed m^{-2}), hairy vetch (20 seed m^{-2}), cereal rye (150 seed m^{-2}), and radish (160 seed m^{-2}). The seeding rate of the mix increased from Years 2 to 3 to improve stand establishment and increase the stand of legume CC. Cover crop planting date and type treatments were applied to the same plots each of the 4 yr and under no-till continuous corn and no-till corn–soybean with each phase present every year at each site.

Corn and soybean were planted with 0.76-m row spacing. Pre-harvest-planted CCs were broadcast by hand and post-harvest-planted CCs were drilled with 18-cm row spacing. Plot size was 6 by12 m at site 1, 4.5 by 9 m at site 2, and 6 by 9 m at site 3. Plot sizes differed due to land availability. We evaluated soil properties in continuous corn and in the corn phase of the corn–soybean rotation. The cereal rye and four-way mix were selected because biomass production was highest with these two CC types, rye is a common CC, and there is strong interest among farmers and researchers in using CC mixes.

2.2 | Soil and cover crop biomass sampling and analysis

Soil samples were collected in June 2018 from the plots under continuous corn and the corn phase of the corn–soybean rotation at all sites. Soil penetration resistance was assessed using a hand cone penetrometer (Eijkelkamp Co., Giesbeek, the Netherlands; Lowery & Morrison, 2002) at six locations within each plot from 0–10- and 10–20-cm soil depths. Penetration resistance readings were converted to cone index, which was then adjusted to a common gravimetric water content by site if correlation between cone index and water content was significant (Blanco-Canqui, Lal, Owens, Post, & Izaurralde, 2005; Busscher, Bauer, Camp, & Sojka, 1997). Soil sorptivity or initial water infiltration was assessed at three locations within each plot. We recorded the amount of time for complete infiltration of 75 ml of water applied within a 9.75 cm diam. ring inserted about 2 cm into the soil and then computed sorptivity (Smith, 1999).

Bulk density, wet-aggregate stability, and concentrations of particulate organic matter, soil organic C, and total N were determined in soil samples collected from 0–5-, 5–10-, and 10–20-cm depths. Ten soil samples were collected from each plot using a 3.1 cm diam. push probe and composited by depth. Total sample mass was recorded and soil bulk density determined through total volume of sample (i.e., the 10 push probe cores carefully sliced at the above depth intervals) and total sample dry mass (Blake & Hartge, 1986). A soil subsample was dried at 105°C for 24 h, weighted, and gravimetric water content calculated. The remaining soil sample was gently crushed and air-dried in a forced-air oven at 65°C for 3 d.

Particulate organic matter, soil organic C, and total N concentrations were measured on air-dried 2-mm sieved soil. Soil organic C and total N concentrations were determined by the dry combustion method on a Flash 2000 C and N analyzer (CE Elantech, Lakewood, NJ) (Nelson & Sommers, 1996). To determine particulate organic matter concentration, 30 g of soil were dispersed with 5 g L^{-1} sodium hexametaphosphate for 24 h and the suspension sieved through 53-μm sieves. The > 53-μm portion was dried at 60°C and ashed at 450°C in a muffle furnace for 4 h. Particulate organic matter concentration was then calculated as the difference between sample mass after drying and after ashing (Cambardella, Gajda, Doran, Wienhold, & Kettler, 2001).

Wet-aggregate stability was determined through wet-sieving (Nimmo & Perkins, 2002) 50 to 51 g of 8-mm sieved soil placed on saturated filter paper (Whatman no. 2) in a stack of nested sieves with openings of 4.75, 2.00, 1.00, 0.50, and 0.25 mm. The sample was rewetted through capillary action for 10 min before removing the filter paper and mechanically sieving the sample in water at 30 oscillations min^{-1} for another 10 min. The contents of each sieve were dried at 105°C for 48 h, weighed, and mean weight diameter of water-stable aggregates calculated.

Cover crop biomass was assessed each spring at termination. All CC biomass within two 0.3 by 1.5 m quadrats was clipped at soil level and dried at 60°C until constant weight. Samples were then weighed and biomass converted to kg ha^{-1} basis. A subsample of the CC biomass was analyzed for organic C concentration by dry combustion and converted to a kg ha^{-1} basis (Gavlak, Horneck, & Miller, 2005). A companion paper will report crop yields and CC biomass production in detail for each year.

2.3 | Statistical analysis

Statistical analysis was conducted by site, crop rotation, and soil depth using PROC MIXED in SAS v. 9.4 for a randomized complete block design (SAS Institute, 2018). Fixed effects were CC planting date and CC type while the random factor was replication. Treatment means separation was through Least Significant Differences (LSD) at the 0.05 probability level. For discussion purposes, we discuss treatment effects by rotation since the three sites used in this study were located in eastern Nebraska under similar precipitation and temperature regimes, soil textures, and slopes (Tables 2 and 3). Only significant ($p < .05$) effects of planting date or CC are discussed. Contrasts were evaluated for the following comparisons: (a) no CC (average of pre-harvest and post-harvest no CC) vs. all others, (b) pre-harvest vs. post-harvest, (c) rye vs. mix, and (d) planting date × CC type (rye or mix). Results from contrasts were similar to LSD pair-wise comparisons in PROC MIXED. Thus, the LSD comparisons from PROC MIXED using the averaged no CCs were used to compare the no CCs to (a) pre-harvest rye, (b) pre-harvest mix, (c) post-harvest rye, and (d) post-harvest mix, which allowed for the investigation of the hypothesized relationship among planting treatments: pre-harvest > post-harvest > no CC. To study relationships among soil properties, we used PROC CORR in SAS for the correlation analysis.

3 | RESULTS

3.1 | Cover crop biomass production

Mean CC biomass production across the 4 yr (2014–2018) of study was affected by planting date in two of the three continuous corn rotations and all three corn–soybean rotations (Table 4). Pre-harvest planting increased CC biomass production by 1.9–3.6 times in two sites and both rotations compared to post-harvest planting. In one site under corn–soybean, however, post-harvest planting increased CC biomass production by 3.1 times. Cover crop type affected CC biomass production in two sites under continuous corn where cereal rye produced 1.8–2.1 times more biomass than CC mix, which was dominated by about 90% cereal rye.

3.2 | Cover crop carbon dynamics

Planting date significantly affected C input from CC biomass (mean across 2014–2018) in two sites under continuous corn (Table 4). Pre–harvest–planted C from CC biomass ranged from 67 to 495 kg ha^{-1} and post-harvest CC biomass C ranged from 57 to 581 kg ha^{-1}. At two sites under continuous corn, pre-harvest-planted CCs had 132 kg ha^{-1} more biomass

TABLE 4 Influence of cover crop (CC) planting date (pre-harvest-planted or post-harvest-planted) and CC type (no, rye, or mix) on CC biomass production and biomass C input averaged across the 4 yr of study in two rotations and at three sites in Nebraska after 4 yr. Different lowercase letters following means within a column denote statistical significance at $p < .05$. No letter denotes non-significant

Treatment	Site 1		Site 2		Site 3	
	Continuous corn	Corn–soybean	Continuous corn	Corn–soybean	Continuous corn	Corn–soybean
	Cover crop biomass production, Mg ha^{-1}					
Pre-harvest–planted CC	0.66a	1.49a	0.80a	1.28a	0.24	0.44b
Post-harvest–planted CC	0.29b	0.69b	0.22b	0.66b	0.23	1.36a
Rye CC	0.55	1.27	0.66a	1.16	0.32a	1.03
Mix CC	0.40	0.92	0.37b	0.78	0.15b	0.77
	Cover crop biomass C input, kg ha^{-1}					
Pre-harvest–planted CC	137.4a	494.9	261.4a	378.5	66.9	113.8
Post-harvest–planted CC	57.8b	249.4	77.5b	202.2	84.6	580.7
Rye CC	166.8a	459.4	214.4	401.3a	116.9	378.5
Mix CC	28.3b	284.8	124.6	179.40b	34.5	315.9

C input than post-harvest-planted CC (Table 4). Cover crop type also affected C input from CC biomass in two sites under continuous corn and corn–soybean. The CC mix C input ranged from 28 to 316 kg ha^{-1} whereas cereal rye C input ranged from 117 to 459 kg ha^{-1}. Across the two sites above, cereal rye CC had 180 kg ha^{-1} more C input than the CC mix.

3.3 | Cover crop planting dates and soil properties

3.3.1 | Comparison with no cover crop

Data using the LSD pair-wise comparisons of pre- or post-harvest planting with no CC are presented in text due to few significant effects. Pre- or post-harvest planting compared to no CC had no effect on soil sorptivity (initial water infiltration), concentrations of total soil N and soil organic C at all three sites and both rotations, but affected cone index, bulk density, wet-aggregate stability, and particulate organic matter, although the effects varied by site and crop rotation. Under continuous corn, pre-harvest planting of the CC mix reduced cone index by 25% (1.29 vs. 1.03 MPa) and bulk density by 7% (1.20 vs. 1.12 Mg m^{-3}) at one of three sites compared to no CC. Under continuous corn, pre-harvest planting of cereal rye increased wet aggregate stability by 27% (2.22 vs. 1.75 mm) at one site. Under corn–soybean, pre-harvest planting of cereal rye increased wet-aggregate stability by 30% (2.03 vs. 1.56 mm) and total particulate organic matter by 46% (15.41 vs. 10.55 g kg^{-1}) at one of three sites. Pre-harvest-planted CCs had no other effects on soil properties compared with no CC.

Similar to pre-harvest planting, post-harvest-planting had few significant effects relative to no CC. Under continuous corn, post-harvest-planted CC mix reduced bulk density by 7% (1.12 vs. 1.20 Mg m^{-3}) and increased cone index by 98% (2.64 vs. 5.23 MPa) at one of three sites compared to no CC. Under corn–soybean, the post-harvest–planted CC mix increased cone index by 59% (2.80 vs. 4.46 MPa) at one of three sites. Post-harvest-planted rye also increased cone index by 40% (2.80 vs. 3.93 MPa) compared to no CC at one site under corn–soybean and increased total particulate organic matter by 33% (13.70 vs. 10.32 g kg^{-1}) at one site under continuous corn.

3.3.2 | Comparison between pre- and post-harvest planting dates

Differences in soil properties between pre- and post-harvest–planted CCs were also few. Pre-harvest-planted CCs had no effect on soil sorptivity and total soil N (data not shown) and soil organic C concentrations (Table 5) compared to post-harvest planting at all sites and rotations. Pre-harvest planting had small, but significant impacts on cone index, bulk density, particulate organic matter concentration, and wet-aggregate stability, expressed as mean weight diameter, compared with post-harvest planting (Table 5; Figure 1). Under continuous corn, pre-harvest-planted CCs reduced cone index by 35% in the 0–10-cm depth at two of three sites. It also increased particulate organic matter concentration by 31% and wet-aggregate stability by 17% in the 0–5-cm depth at one site. Under corn–soybean, pre-harvest-planted CCs reduced bulk density in the 0–5-cm depth at one site. Planting date did not affect cone index at the 10–20-cm depth except at one site under continuous corn where post-harvest–planted CCs increased cone index by 9% (1.93 vs. 1.77 MPa). In the 5–10-cm depth, pre-harvest planting increased wet-aggregate stability in one continuous corn and one corn–soybean rotation. Pre-harvest-planted CCs had no other effects on soil properties compared to post-harvest-planted CCs.

TABLE 5 Influence of planting date (pre-harvest-planted vs post-harvest-planted) and CC type (no, rye, or mix) on sorptivity, soil organic C concentration, cone index, bulk density, and total particulate organic matter concentration in two rotations and at three sites in Nebraska after 4 yr. Different lowercase letters following means within planting date or CC type in a column denote statistical significance at $p < .05$. No letter denotes non-significant

Treatment	Site 1		Site 2		Site 3	
	Continuous corn	Corn–soybean	Continuous corn	Corn–soybean	Continuous corn	Corn–soybean
	Sorptivity, cm s$^{-1/2}$					
Pre-harvest–planted CC	0.20	0.17	0.16	0.22	0.12	0.14
Post-harvest–planted CC	0.20	0.18	0.26	0.25	0.13	0.14
No CC	0.19	0.17	0.29	0.24	0.12	0.15
Rye CC	0.19	0.18	0.13	0.26	0.11	0.13
Mix CC	0.21	0.18	0.22	0.22	0.14	0.14
	Soil organic C, g kg^{-1}					
	0–5-cm depth					
Pre-harvest–planted CC	30.7	29.7	19.4	21.5	22.9	21.0
Post-harvest–planted CC	29.9	29.5	20.2	22.0	24.7	20.8
No CC	30.1	29.4	20.0	21.1	24.6	21.0
Rye CC	30.0	29.5	19.8	21.7	23.2	22.3
Mix CC	30.8	29.9	19.7	22.3	23.5	19.3
	Cone index, MPa					
	0–10-cm depth					
Pre-harvest–planted CC	1.21	1.13	1.56b	1.80	2.36b	3.59
Post-harvest–planted CC	1.22	1.18	2.04a	1.91	3.26a	3.26
No CC	1.29a	1.18a	1.76	1.81	2.64b	2.80b
Rye CC	1.24a	1.21a	1.74	1.83	2.01b	3.34ab
Mix CC	1.11b	1.07b	1.88	1.91	3.80a	4.14a
	Bulk density, Mg m^{-3}					
	0–5-cm depth					
Pre-harvest–planted CC	1.10	1.08a	1.24	1.29	1.18	1.27
Post-harvest–planted CC	1.03	1.02b	1.28	1.27	1.14	1.21
No CC	1.10	1.07	1.29	1.27	1.20a	1.23
Rye CC	1.08	1.04	1.26	1.28	1.16ab	1.23
Mix CC	1.01	1.04	1.23	1.29	1.12b	1.26
	Total particulate organic matter, g kg^{-1}					
	0–5-cm depth					
Pre-harvest–planted CC	19.7a	16.9	11.0	12.6	14.6	14.4
Post-harvest–planted CC	15.0b	20.4	12.3	11.8	14.4	13.1
No CC	16.5	17.4	10.3	10.6	15.8	15.5
Rye CC	17.8	20.9	12.6	14.7	13.4	12.4
Mix CC	17.8	17.9	12.0	11.4	14.3	13.8

3.4 | Cover crop mixes and changes in soil properties

Cover crop mixes had no effect on soil sorptivity and total soil N (data not shown), soil organic C, and particulate organic matter concentrations (Table 5) compared to no CC all three sites and both rotations. Cover crop mixes did, however, influence cone index, bulk density (Table 5), and wet-aggregate stability expressed as mean weight diameter (Figure 1) at some sites compared to no CC. Under continuous corn, CC mixes reduced cone index by 16% and increased it by 44% at two sites compared to no CC at the 0–10-cm depth. In the same rotation, mixes also reduced bulk density by 7% relative to no CC for the 0–5-cm depth. Under corn–soybean, CC mixes reduced cone index by 10% and increased it by 48% at two sites compared to no CC. They also increased

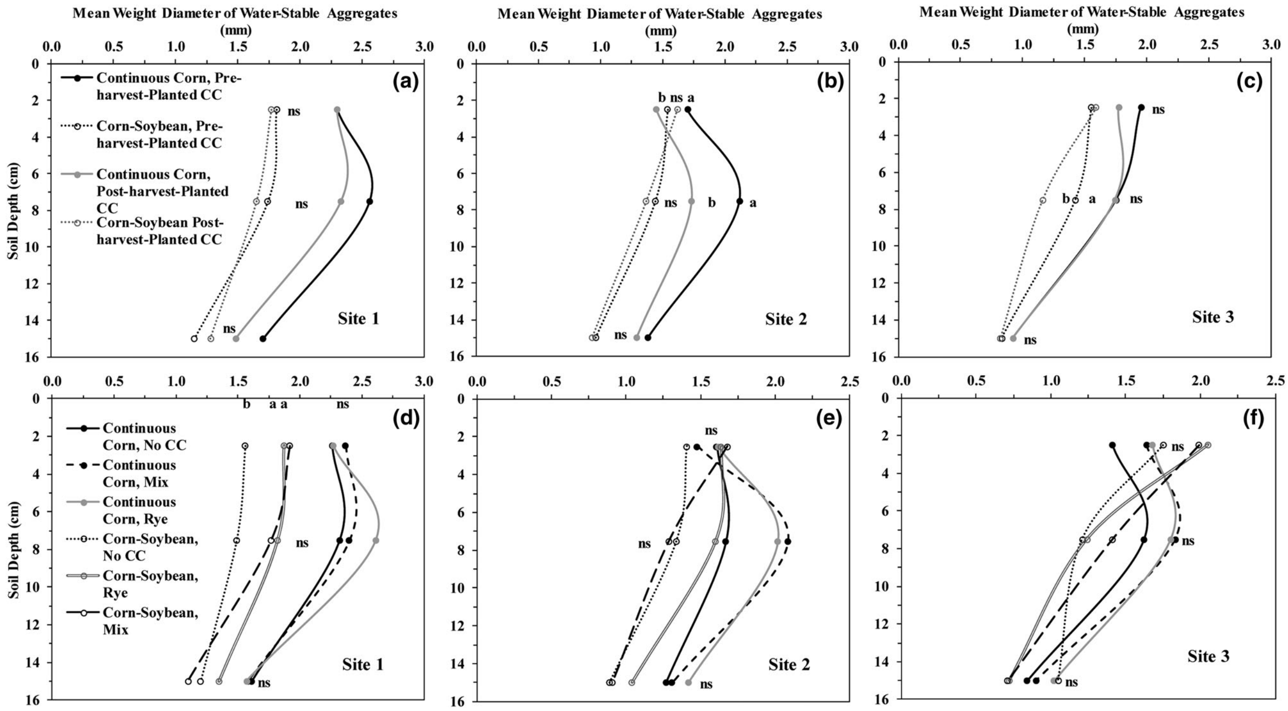

FIGURE 1 Influence of (a–c) cover crop (CC) planting date (pre-harvest or post-harvest) and (d–f) CC type (no, rye or mix) on mean weight diameter of water-stable aggregates in continuous corn and corn–soybean at three sites in Nebraska. ns denotes non-significant. Different lowercase letters within a cropping system and depth interval denote statistical differences at $p < .05$

wet-aggregate stability by 21% at one site for the same rotation.

Cereal rye had no effect on soil sorptivity and total soil N (data not shown), cone index, bulk density, soil organic C, and particulate organic matter concentrations (Table 5) compared to no CC at all sites and rotations. Cereal rye increased wet-aggregate stability by 20% compared to no CC at one site under corn–soybean rotation (Figure 1). Compared to mixes, cereal rye increased cone index by 12.5% at one site in both rotations and reduced cone index by 89% at one site under continuous corn. Cover crop type had no other effects on soil properties.

4 | DISCUSSION

4.1 | Cover crop biomass production

Cover crop biomass production in this study was, in general, low. The higher CC biomass production for pre-harvest-planted CCs compared to post-harvest-planted CCs at two sites was likely due to the longer growing season (about 1.5–2 mo), which provided more optimum temperature and moisture conditions for growth. While pre-harvest planting did improve CC biomass production at two of three sites in both rotations, it was typically below 1 Mg ha^{-1}. Other studies in the region observed biomass production of 2.92–4.19 Mg ha^{-1} depending on species (Nielsen, Lyon, Hergert, Higgins, & Holman, 2015b), 0.26–0.51 Mg ha^{-1} if terminated in mid-April, 1.60–2.85 Mg ha^{-1} if terminated in late April–early May (Ruis et al., 2017), 0.80 Mg ha^{-1} planted following corn harvest (Blanco-Canqui et al., 2014), and 1.47 Mg ha^{-1} if planted in September into corn (Blanco-Canqui, Sindelar, Wortmann, & Kreikemeier, 2017; Ruis et al., 2019). This means average CC biomass production in the region may be about 1.8 Mg ha^{-1}, which is above the CC biomass production in our study (<1 Mg ha^{-1}). The overall low CC biomass was potentially due to a variety of factors including relatively early termination and later seeding, among others.

The higher CC biomass production across the 4 yr (2014–2018) with post-harvest planting compared to pre-harvest planting at site 3 under corn–soybean was potentially due to the lower amount of residue produced under soybean. Based on grain and stover yield from a nearby experiment, corn residue amount ranged from 11.5 to 16.0 Mg ha^{-1} at site 3 under continuous corn (Ruis et al., 2017), but soybean residue amount may range from 3.7 to 6.9 Mg ha^{-1} (Xie, Schoenau, & Warkentin, 2018). The lower residue amount under the corn–soybean rotation may have led to warmer temperatures (Kenney et al., 2015) for CC germination and better seed-soil contact under drill seeding (post-harvest planting). The overall CC biomass production among the three sites was similar, which reflects the similarities in climate among the three sites.

4.2 | Cover crop carbon dynamics

Despite the addition of up to 495 kg ha^{-1} of C from the CCs (Table 4), pre-harvest-planted CCs did not accumulate more soil organic C than no CCs (Table 5). This leads to the question: What happened to the 495 kg ha^{-1} of C input? The C from CC biomass was likely lost through microbial respiration or decomposition, which may occur quickly after CC termination. Previous research on CC decomposition showed that about 70–75% of the CC mass is lost within a 10 (Rosenzweig, Schipanski, & Kaye, 2017)−16-wk (Sievers & Cook, 2018) period, and about 79% after 1 yr (de Sa Pereira, Galantini, & Duval, 2017). Therefore, if we assume that the highest C input of 495 kg ha^{-1} from our CCs (Table 4) decomposed by 75% over the course of a year, about 124 kg ha^{-1} C would remain. This means the maximum C increase would be about 0.124 Mg ha^{-1} in a soil that already contains about 18 Mg ha^{-1}, a negligible amount. Averaged across all pre-harvest-planted CCs, about 0.059 Mg C ha^{-1} remains after 1 yr, which is about 0.32% of the soil C, indicating that the estimated change in soil C would be very small and masked by the inherent variability of soil.

Further, CC biomass in these no-till systems is left on the soil surface which can lead to the stratification of C concentration in the soil profile. We sampled the upper 0–5 cm of the soil, but C gains due to CCs may be diluted within that sampling depth. On a nearby experiment, after 3 yr, Blanco-Canqui et al. (2014) reported that rye CC, which produced 0.80 Mg ha^{-1} of biomass across the 3 yr, increased soil organic C in the 0–2.5 cm of the soil, but not in the 2.5–5-cm depth. For the same experiment, Sindelar, Blanco-Canqui, Jin, and Ferguson (2019) found that even after 6 yr, C accumulation due to CCs was not detectable in the upper 5 cm of the soil.

4.3 | Cover crop planting dates and soil properties

The minimal differences among CC planting date treatments could be due to low CC biomass production, even though the mean biomass production across the 4 yr for pre-harvest planting (0.81 Mg ha^{-1}) was about 37% higher than post-harvest planting (0.59 Mg ha^{-1}). A CC study on a site nearby found that sites with similar C contents may show no effects on soil properties after 3 yr of management even with 4.1 Mg ha^{-1} of biomass (Ruis et al., 2017). These soils, with organic matter contents near what is considered an "ideal" soil (Brady, 1990), are generally slow to change with management. The high organic matter content and short-term nature of the project (4 yr) could also be potential reasons why differences in soil properties were few. For example, a review that discussed CC effects on soil C showed that the change in soil organic C stocks was typically small in the first 5 yr after CC adoption (Ruis & Blanco-Canqui, 2017). Similarly, changes in wet-aggregate stability were generally lower in the first 5 yr after no-till adoption compared to conventional tillage (Blanco-Canqui & Ruis, 2018). Management strategies that increase CC biomass, such as further extending CC growing seasons, and more time with CC integrated into the cropping system, may be required for changes to soil properties to occur.

Cover crop planting date generally had more impact in the continuous corn than corn–soybean rotation. For example, CC planting date improved soil properties at four site-rotations (two for reduced cone index, one for particulate organic matter, and one for wet-aggregate stability) under continuous corn compared to one site-rotation for corn–soybean. The greater impacts under continuous corn were potentially due to the difference in residue quality between corn and the CCs (high C/N ratio for corn residue and lower C/N ratio for CCs) and subsequent changes in the microbial community. While additional data would be required to confirm this, data on diversified cropping systems suggest that the use of contrasting crops can improve soil microbial communities (Liebig, Carpenter-Boggs, Johnson, Wright, & Barbour, 2006).

4.4 | Cover crop mixes and changes in soil properties

The higher cone index with the mix CC at the site 3 may be due to the lower water content (data not shown) under this treatment. Although data on cone index were corrected for differences in water content, the increased cone index under the CC mix would suggest that the corrective equation may have some limitations (Busscher et al., 1997). The minimal effects of CC type (mix vs. single species cereal rye vs. no CC) were not surprising because of the low biomass production for both rye and the mix (0.57 ± 0.42 Mg ha^{-1}) and rye (0.83 ± 0.52 Mg ha^{-1}). Cover crop type effects on soil properties did not generally vary between the two cropping systems (continuous corn and corn–soybean) and sites (Figure 1; Table 5).

The lack of effects of CC mixes on soil physical properties (sorptivity, compaction parameters, and aggregate stability) in this study after 4 yr was not entirely surprising as physical properties are often slow to change with management (Irmak et al., 2018). Our results of limited changes in soil physical properties under CC mix generally agree with previous studies summarized in Table 1. The limited effects of mixes were potentially due to a combination of mix composition, management, and low biomass production. For example, mixing a fibrous-rooted species such as Austrian winter pea with a

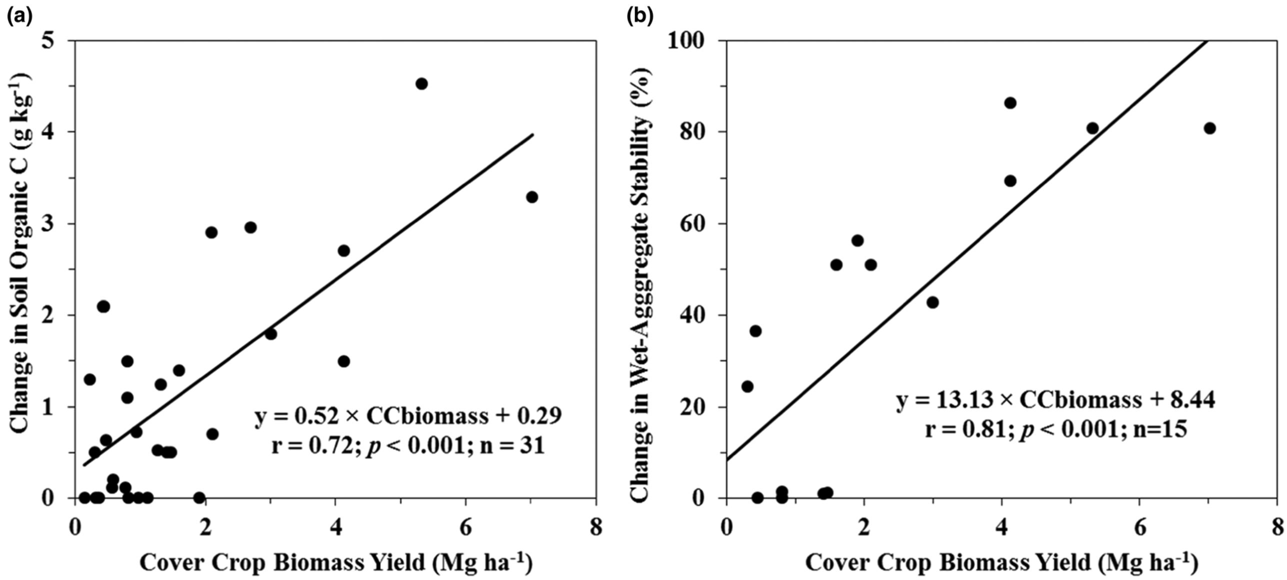

FIGURE 2 (a) Relationship between change in soil C (cover crop soil C minus no cover crop soil C) and cover crop (CC) biomass production and (b) change in wet-aggregate stability and CC biomass production. Data from Blanco-Canqui et al. (2011, 2013, 2014, 2017); Kaspar et al. (2006); Moore et al. (2014); Rorick and Kladivko (2017); Ruis et al. (2017); and Sindelar et al. (2019)

tap-rooted species such as radish may reduce soil bulk density compared to radish alone as the roots of fibrous-rooted species can have better contact with the soil matrix, possibly promoting better aggregation (Table 1, Stavi, Lal, Jones, & Reeder, 2012). Thus, we may not have observed effects of the mix on compaction parameters in this study as our mix was dominated by cereal rye (about 90% rye), a fibrous-rooted species, and was comparable to cereal rye alone. However, with some soil properties, such as wet-aggregate stability, even diverse species combinations or root architecture may not have an impact (Table 1; Acuna & Villamil, 2014).

The findings from our study and the review in Table 1 can have implications for CC management and suggest that the additional seed cost of the CC mix may not be warranted as suggested by some previous research in the region (Nielsen et al., 2015a). Cover crop mixes may not improve soil properties more than single species if they produce similar amounts of biomass. For instance, two studies in the region showed that CC mixes and single species did not differ in total CC biomass production (Nielsen et al., 2015a, 2015b; Wortman et al., 2012) or water use (Nielsen et al., 2015a, 2015b).

4.5 | Interrelationships between cover crop biomass production and soil properties

Cover crop biomass production can be key to exerting changes in soil properties. In this study, however, CC biomass production was not correlated with soil properties at any site nor across sites (data not shown). To better understand how CC biomass input can affect soil properties, we reviewed published studies and performed correlations of CC biomass with select soil properties such as changes in soil C concentration (no CC minus CC) and soil wet-aggregate stability (percent change between no CC and CC). These results showed that CC biomass production was strongly and linearly correlated with changes in soil organic C concentration (r = .72; p < .001; n = 31; Figure 2A) across 10 studies, and with changes in wet-aggregate stability (r = .81; p < .001; n = 15; Figure 2B) across eight studies. The relationships indicate that as CC biomass yield increases, soil organic C concentration and wet-aggregate stability increase. However, note in Figure 2A–2B that when biomass production is <2 Mg ha^{-1}, as in our study, changes in soil organic C concentration and wet-aggregate stability may be small or not significant. The lack of change in soil C and wet-aggregation when biomass production is low clearly highlights the role of CC biomass amount in dictating changes in soil properties. Increasing residue input to a cropping system can improve soil aggregation and lead to greater proportions of larger aggregates (Stetson et al., 2012). The increased wet-aggregate stability can alter pore-size distribution leading to increased macroporosity and thus increased infiltration and reduced compaction risks in the long-term (Blanco-Canqui, Stone, & Stahlman, 2010).

Correlations among soil properties by site in the present study were generally not significant. At site 1, bulk density and particulate organic matter were negatively correlated (r = –.32, p = .03), and sorptivity (initial water infiltration) was positively correlated with both soil organic C (r = .37, p = .01) and total N concentrations (r = .34, p = .02). There were no significant correlations for the site 2. At the site 3, wet-aggregate stability (r = .32, p = .03) and total particulate organic matter concentration (r = .30, p = .04) were positively correlated with total N concentration. The positive correlations between soil organic matter parameters and wet-aggregate stability, although few, corroborate the important role of soil organic matter in contributing to soil aggregation (Six, Paustian, Elliott, & Combrink, 2000).

5 | CONCLUSIONS

This study evaluated CC planting date and CC type effects on soil properties in corn and corn−soybean rotations at three sites in Nebraska after 4 yr and showed limited CC planting date and CC type impacts on soil properties. Pre-harvest–planted CCs did not generally induce large effects on soil properties compared to post-harvest–planted CCs or no CC. Mixes and single species also had limited effects on soil properties, likely due to low biomass production (< 1 Mg ha^{-1}). Our literature review also showed that mixes generally did not show greater improvements in soil properties compared to single species. Relationships of CC biomass production and soil C concentration or wet-aggregate stability across studies in our literature review showed that CC biomass production must be sufficiently large, likely >3 Mg ha^{-1}, to induce detectable changes in these soil properties. Cover crop C input to the soil, in our study, was small compared to the total soil C. It appears that if improvement in soil properties is desired, then alternative CC management strategies may be required to increase biomass production. Furthermore, we suggest that, in addition to the small or no effects on soil properties, CCs may have limited effects on delivering other ecosystem services (i.e, weed suppression) in this region if CC biomass production is low. Overall, pre-harvest planting and mixes, compared to post-harvest planting and cereal rye, had limited effects on improving soil properties in three sites under similar soil and climatic conditions in the eastern Great Plains in the short term (4 yr).

ACKNOWLEDGEMENTS

The authors would like to acknowledge the funding from the Nebraska Corn Board and Nebraska Soybean Board to accomplish this project and was part of the project "Implementation of cover crops in Nebraska corn and soybean systems." The authors would also like to thank two summer research interns: Emma Richmond-Boudewyns and Julie McDowell for their assistance in soil sample and data collection. The authors also wish to thank George Biliarski, Tom Galusha, Mike Mainz, Jeremy Milander, Mike Schlick, and Caleb Wilford for their technical assistance.

ORCID

Sabrina J. Ruis https://orcid.org/0000-0002-8769-9453
Humberto Blanco-Canqui https://orcid.org/0000-0002-9286-8194
Katja Koehler-Cole https://orcid.org/0000-0003-4150-6254
Charles A. Shapiro https://orcid.org/0000-0002-0011-7618

REFERENCES

Acuna, J. C., & Villamil, M. B. (2014). Short-term effects of cover crops and compaction on soil properties and soybean production in Illinois. *Agronomy Journal*, *106*, 860–970. Retrieved from https://doi.org/10.2134/agronj13.0370

Appelgate, S. R., Lenssen, A. W., Wiedenhoeft, M. H., & Kaspar, T. C. (2017). Cover crop options and mixes for Upper Midwest corn–soybean systems. *Agronomy Journal*, *109*, 968–984. Retrieved from https://doi.org/10.2134/agronj2016.08.0453

Balkcom, K. S., Massey, J. M., Mosjidis, J. A., Price, A. J., & Enloe, S. F. (2011). Planting date and seeding rate effects on sunn hemp biomass and nitrogen production for a winter cover crop. *International Journal of Agronomy*, *2011*, 1–8. Retrieved from https://doi.org/10.1155/2011/237510

Barker, J. B., Heeren, D. M., Koehler-Cole, K., Shapiro, C. A., Blanco-Canqui, H., Elmore, R. W., … Mohammed, A. T. (2018). Cover crops have negligible impact on soil water in Nebraska maize-soybean rotation. *Agronomy Journal*, *110*, 1718–1730. Retrieved from https://doi.org/10.2134/agronj2017.12.0739

Blake, G. R., & Hartge, K. H. (1986). Bulk density. In A. Klute (Ed.), *Methods of soil analysis: Part -Physical and mineralogical methods* (pp. 363–375). 2nd ed. Agronomy Monograph 9. Madison, WI: American Society of America and Soil Science Society of America.

Blanco-Canqui, H., Ferguson, R. B., Jin, V. L., Schmer, M. R., Wienhold, B. J., & Tatarko, J. (2014). Can cover crop and manure maintain soil properties after stover removal from irrigated no-till corn? *Soil Science Society of America Journal*, *78*, 1368–1377. Retrieved from https://doi.org/10.2136/sssaj2013.12.0550

Blanco-Canqui, H., & Francis, C. A. (2016). Building resilient soils through agroecosystem redesign under fluctuating climatic regimes. *Journal of Soil and Water Conservation*, *71*, 127A–133A. Retrieved from https://doi.org/10.2489/jswc.71.6.127A

Blanco-Canqui, H., Holman, J. D., Schlegel, A. J., Tatarko, J., & Shaver, T. M. (2013). Replacing fallow with cover crops in a semiarid soil: Effects on soil properties. *Soil Science Society of America Journal*, *77*, 1026–1034. Retrieved from https://doi.org/10.2136/sssaj2013.01.0006

Blanco-Canqui, H., Lal, R., Owens, L. B., Post, W. M., & Izaurralde, R. C. (2005). Strength properties and organic carbon of soils in the North Appalachian Region. *Soil Science Society of America Journal*, *69*, 663–673. Retrieved from https://doi.org/10.2136/sssaj2004.0254

Blanco-Canqui, H., Mikha, M. M., Presley, D. R., & Claassen, M. M. (2011). Addition of cover crops enhances no-till potential for improving soil physical properties. *Soil Science Society of America Journal*, *75*, 1471–1482. Retrieved from https://doi.org/10.2136/sssaj2010.0430

Blanco-Canqui, H., & Ruis, S. J. (2018). No-till and the soil physical environment. *Geoderma*, *326*, 164–200. Retrieved from https://doi.org/10.1016/j.geoderma.2018.03.011

Blanco-Canqui, H., Shaver, T. M., Lindquist, J. L., Shapiro, C. A., Elmore, R. W., Francis, C. A., & Hergert, G. W. (2015). Cover crops and ecosystem services: Insights from studies in temperate soils. *Agronomy Journal*, *107*, 2449–2474. Retrieved from https://doi.org/10.2134/agronj15.0086

Blanco-Canqui, H., Sindelar, M., Wortmann, C. S., & Kreikemeier, G. (2017). Aerial interseeded cover crop and corn residue harvest: Soil and crop impacts. *Agronomy Journal*, *109*, 344–1351. Retrieved from https://doi.org/10.2134/agronj2017.02.0098

Blanco-Canqui, H., Stone, L. R., & Stahlman, P. W. (2010). Soil response to long-term cropping systems on an Argiustoll in the Central Great Plains. *Soil Science Society of America Journal*, *74*, 602–611. Retrieved from https://doi.org/10.2136/sssaj2009.0214

Brady, N. C. 1990. The nature and properties of soils. (10th Ed.). New York, NY: Macmillan Publishing Company.

Busscher, W. J., Bauer, P. J., Camp, C. R., & Sojka, R. E. (1997). Correction of cone index for soil water content differences in a coastal plain soil. *Soil and Tillage Research*, *43*, 205–217. Retrieved from https://doi.org/10.1016/S0167-1987(97)00015-9

Cambardella, C. A., Gajda, A. M., Doran, J. W., Wienhold, S. B. J., & Kettler, T. A. (2001). Estimation of particulate and total organic matter by weight loss-on-ignition. In R. Lal (Ed.), *Assessment methods for soil carbon* (pp. 349–359). Boca Raton, FL: Lewis Publishers.

Chu, M., Jagadamma, S., Walker, F. R., Eash, N. S., Buschermohle, M. J., & Duncan, L. A. (2017). Effect of multispecies cover crop mixture on soil properties and crop yield. *Agricultural & Environmental Letters*, *2*, 170020.

Curran, W. S., Hoover, R. J., Mirsky, S. B., Roth, G. W., Ryan, M. R., Ackroyd, V. J., … Pelzer, C. J. (2018). Evaluation of cover crops drill interseeded into corn across the Mid-Atlantic region. *Agronomy Journal*, *110*, 435–443. Retrieved from https://doi.org/10.2134/agronj2017.07.0395

de Sa Pereira, E., Galantini, J. A., & Duval, M. E. (2017). Use of a three-compartment model to evaluate the dynamics of cover crop residues. *Archives of Agronomy and Soil Science*, *63*, 1623–1629. Retrieved from https://doi.org/10.1080/03650340.2017.1296137

Ding, G., Liu, X., Herbert, S., Novak, J., Amarasriwardena, D., & Xing, B. (2006). Effect of cover crop management on soil organic matter. *Geoderma*, *130*, 229–239. Retrieved from https://doi.org/10.1016/j.geoderma.2005.01.019

Duiker, S. W. (2014). Establishment and termination dates affect fall-established cover crops. *Agronomy Journal*, *106*, 670–678. Retrieved from https://doi.org/10.2134/agronj2013.0246

Duval, M. E., Galantini, J. A., Capurro, J. E., & Martinez, J. M. (2016). Winter cover crops in soybean monoculture: Effects on soil organic carbon and its fractions. *Soil and Tillage Research*, *161*, 95–105. Retrieved from https://doi.org/10.1016/j.still.2016.04.006

Finney, D. M., White, C. M., & Kaye, J. P. (2016). Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. *Agronomy Journal*, *108*, 39–52. Retrieved from https://doi.org/10.2134/agronj15.0182

Gavlak, R., Horneck, D., & Miller, R. O. (2005). Nitrogen and sulfur. In *Soil, plant and water reference methods for the western region* (pp. 150–155). 3rd ed. Retrieved from https://www.naptprogram.org/files/napt/western-states-method-manual-2005.pdf

Hashemi, M., Farsad, A., Sadeghpour, A., Weis, S. A., & Herbert, S. J. (2013). Cover-crop seeding-date influence on fall nitrogen recovery. *Journal of Plant Nutrition and Soil Science*, *176*, 69–75. Retrieved from https://doi.org/10.1002/jpln.201200062

Hayden, Z. D., Ngouajio, M., & Brainard, D. C. (2015). Planting date and staggered seeding of rye-vetch mixtures: Biomass, nitrogen, and legume winter survival. *Agronomy Journal*, *107*, 33–40. Retrieved from https://doi.org/10.2134/agronj14.0237

Holman, J. D., Arnet, K., Dille, J., Maxwell, S., Obour, A., Roberts, T., … Schlegel, A. (2018). Can cover or forage crops replace fallow in the semiarid central Great Plains? *Crop Science*, *58*, 1–13. Retrieved from https://doi.org/10.2135/cropsci2017.05.0324

Hunter, M. C., Schipanski, M. E., Burgess, M. H., LaChance, J. C., Bradley, B. A., Barbercheck, M. E., … Mortensen, D. A. (2019). Cover crop mixture effects on maize, soybean, and wheat yield in rotation. *Agricultural & Environmental Letters*, *4*, 180051.

Irmak, S., Sharma, V., Mohammed, A. T., & Djaman, K. (2018). Impacts of cover crops on soil physical properties: Field capacity, permananet wilting point, soil-water holding capacity, bulk density, hydraulic conductivity, and infiltration. *Transactions ASABE*, *61*, 1307–1321. Retrieved from https://doi.org/10.13031/trans.12700

Kaspar, T. C., Parkin, T. B., Jaynes, D. B., Cambardella, C. A., Meek, D. W., & Jung, Y. S. (2006). Examining changes in soil organic carbon with oat and rye cover crops using terrain covariates. *Soil Science Society of America Journal*, *70*, 1168–1177. Retrieved from https://doi.org/10.2136/sssaj2005.0095

Kenney, I., Blanco-Canqui, H., Presley, D. R., Rice, C. W., Janssen, K., & Olson, B. (2015). Soil and crop response to stover removal from rainfed and irrigated corn. *GCB Bioenerg*, *7*, 219–230. Retrieved from https://doi.org/10.1111/gcbb.12128

Lawson, A., Cogger, C., Bary, A., & Fortuna, A. M. (2015). Influence of seeding ratio, planting date, and termination date on rye-hairy vetch cover crop mixture performance under organic management. *Plos One*, *10*, e0129597. Retrieved from https://doi.org/10.1371/journal.pone.0129597

Lewis, K. L., Burke, J. A., Keeling, W. S., McCallister, D. M., DeLaune, P. B., & Keeling, J. W. (2018). Soil benefits and yield limitation of cover crop use in Texas High Plains cotton. *Agronomy Journal*, *100*, 1616–1623. Retrieved from https://doi.org/10.2134/agronj2018.02.0092

Liebig, M., Carpenter-Boggs, L., Johnson, J. M. F., Wright, S., & Barbour, N. (2006). Cropping system effects on soil biological characteristics in the Great Plains. *Renewable Agriculture and Food Systems*, *21*, 36–48. Retrieved from https://doi.org/10.1079/RAF2005124

Liebman, A. M., Grossman, J., Brown, M., Wells, S., Reberg-Horton, S. C., & Shi, W. (2018). Legume cover crop and tillage impact nitrogen dynamics in organic corn production. *Agronomy Journal*, *110*, 1–12. Retrieved from https://doi.org/10.2134/agronj2017.08.0474

Lowery, B., & Morrison, J. E. (2002). Soil penetrometers and penetrability. In J. H. Dane & G. C. Topp (Eds.), *Methods of soil analysis* (pp. 363–385). Part 4. SSSA Soil Ser. 5. Madison, WI: Soil Science Society of America.

Moore, E. B., Wiedenhoeft, M. H., Kaspar, T. C., & Cambardella, C. A. (2014). Rye cover crop effects on soil quality in no-till corn silage-soybean cropping systems. *Soil Science Society of America Journal*, *78*, 968–976. Retrieved from https://doi.org/10.2136/sssaj2013.09.0401

Murrell, E. G., Schipanski, M. E., Finney, D. M., Hunter, M. C., Burgess, M., LaChance, J. C., … Kaye, J. P. (2017). Achieving diverse cover crop mixtures: Effects of planting date and seeding rate. *Agronomy Journal*, *109*, 259–271. Retrieved from https://doi.org/10.2134/agronj2016.03.0174

Nelson, D. W., & Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter: Laboratory methods. In D. L. Sparks (Ed.), *Methods of soil analysis* (pp. 961–1010). Part 3. SSSA Book Ser. 5. Madison, WI: Soil Science Society of America.

Nielsen, D. C., Lyon, D. J., Hergert, G. W., Higgins, R. K., Calderon, F. J., & Vigil, M. F. (2015a). Cover crop mixtures do not use water differently than single-species plantings. *Agronomy Journal*, *107*, 1025–1038. Retrieved from https://doi.org/10.2134/agronj14.0504

Nielsen, D. C., Lyon, D. J., Hergert, G. W., Higgins, R. K., & Holman, J. D. (2015b). Cover crop biomass production and water use in the central Great Plains. *Agronomy Journal*, *107*, 2047–2058. Retrieved from https://doi.org/10.2134/agronj15.0186

Nimmo, J. R., & Perkins, K. S. (2002). Aggregate stability and size distribution. In J. H. Dane & G. C. Topp (Eds.), *Methods of soil analysis* (pp. 317–327). Part 4. SSSA Book Ser. 5. Madison, WI: Soil Science Society of America.

Noland, R. L., Wells, M. S., Sheaffer, C. C., Baker, J. M., Martinson, K. L., & Coulter, J. A. (2018). Establishment and function of cover crops interseeded into corn. *Crop Science*, *58*, 863–873. Retrieved from https://doi.org/10.2135/cropsci2017.06.0375

Nunes, M. R., van Es, H. M., Schindelbeck, R., Ristow, A. J., & Ryan, M. (2018). No-till and cropping system diversification improve soil health and crop yield. *Geoderma*, *328*, 30–43. Retrieved from https://doi.org/10.1016/j.geoderma.2018.04.031

Parr, M., Grossman, J. M., Reberg-Horton, S. C., Brinton, C., & Crozier, C. (2011). Nitrogen delivery from legume cover crops in no-till organic corn production. *Agronomy Journal*, *103*, 1578–1590. Retrieved from https://doi.org/10.2134/agronj2011.0007

Rorick, J. D., & Kladivko, E. J. (2017). Cereal rye cover crop effects on soil carbon and physical properties in southeastern Indiana. *Journal of Soil and Water Conservation*, *72*, 260–265. Retrieved from https://doi.org/10.2489/jswc.72.3.260

Rosenzweig, S. T., Schipanski, M. E., & Kaye, J. P. (2017). Rhizosphere priming and plant-mediated cover crop decomposition. *Plant and Soil*, *417*, 127–139. Retrieved from https://doi.org/10.1007/s11104-017-3246-5

Ruis, S., & Blanco-Canqui, H. (2017). Cover crops could offset crop residue removal effects on soil carbon and other soil properties: A review. *Agronomy Journal*, *109*, 1785–1805. Retrieved from https://doi.org/10.2134/agronj2016.12.0735

Ruis, S., Blanco-Canqui, H., Creech, C., Koehler-Cole, K., Elmore, R., & Francis, C. (2019). Cover crop biomass production in temperate agroecozones. *Agronomy Journal*, *111*, 1–17. Retrieved from https://doi.org/10.2134/agronj2018.08.0535

Ruis, S. J., Blanco-Canqui, H., Jasa, P. J., Ferguson, R. B., & Slater, G. (2017). Can cover crop use allow increased levels of corn residue removal for biofuel in irrigated and rainfed systems? *BioEnergy Research*, *10*, 992–1004. Retrieved from https://doi.org/10.1007/s12155-017-9858-z

SAS Institute. (2018). SAS OnlineDoc 9.1.3. Cary, NC: SAS Institute. support.sas.com/onlinedoc/913/docMainpage.jsp

Sharma, V., Irmak, S., & Padhi, J. (2018). Effects of cover crops on soil quality: Part I. Soil chemcial properties-organic carbon, total nitrogen, pH, electical conductivity, organic matter content, nitrate-nitrogen, and phosphorus. *Journal of Soil and Water Conservation*, *73*, 637–651. Retrieved from https://doi.org/10.2489/jswc.73.6.637

Sievers, T., & Cook, R. L. (2018). Aboveground and root decomposition of cereal rye and hairy vetch cover crops. *Soil Science Society of America Journal*, *82*, 147–155. Retrieved from https://doi.org/10.2136/sssaj2017.05.0139

Sindelar, M., Blanco-Canqui, H., V., Jin, & Ferguson, R. (2019). Cover crops and corn residue removal: Impacts on soil hydraulic properties and their relationships with carbon. *Soil Science Society of America Journal*, *83*, 221–231. Retrieved from https://doi.org/10.2136/sssaj2018.06.0225

Six, J., Paustian, K., Elliott, E. T., & Combrink, C. (2000). Soil structure and organic matter I. Distribution of aggregate-size classes and aggregate-associated carbon. *Soil Science Society of America Journal*, *64*, 681–689. Retrieved from https://doi.org/10.2136/sssaj2000.642681x

Smith, R. E. (1999). Technical note: Rapid measurement of soil sorptivity. *Soil Science Society of America Journal*, *63*, 55–57. Retrieved from https://doi.org/10.2136/sssaj1999.03615995006300010009x

Smith, R. G., Atwood, L. W., & Warren, N. D. (2014). Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. *Plos One*, *9*, e97351. Retrieved from https://doi.org/10.1371/journal.pone.0097351

Stavi, I., Lal, R., Jones, S., & Reeder, R. C. (2012). Implications of cover crops for soil quality and geodiversity in a humid-temperate region in the Midwestern USA. *Land Degradation and Development*, *23*, 322–330. Retrieved from https://doi.org/10.1002/ldr.2148

Stetson, S. J., Osborne, S. L., Schumacher, T. E., Eynard, A., Chilom, G., Rice, J., … Pikul, J. L., Jr (2012). Corn residue removal impact on topsoil organic carbon in a corn-soybean rotation. *Soil Science Society of America Journal*, *76*, 1399–1406. Retrieved from https://doi.org/10.2136/sssaj2011.0420

USDA_NASS. (2018). Quick stats. United States Department of Agriculture. Washington, DC: National Agricultural Statistics Services. Retrieved from https://quickstats.nass.usda.gov/

Villamil, M. B., Bollero, G. A., Darmody, R. G., Simmons, F. W., & Bullock, D. G. (2006). No-till corn/soybean systems including winter cover crops: Effects on soil properties. *Soil Science Society of America Journal*, *70*, 1936–1944. Retrieved from https://doi.org/10.2136/sssaj2005.0350

Wilson, M. L., Baker, J. M., & Allan, D. L. (2013). Factors affecting successful establishment of aerially seeded winter rye. *Agronomy Journal*, *105*, 1868–1877. Retrieved from https://doi.org/10.2134/agronj2013.0133

Wortman, S. E., Francis, C. A., & Lindquist, J. L. (2012). Cover crop mixtures for the western corn belt: Opportunities for increased productivity and stability. *Agronomy Journal*, *104*, 699–705. Retrieved from https://doi.org/10.2134/agronj2011.0422

Xie, J., Schoenau, J., & Warkentin, T. D. (2018). Yield and uptake of nitrogen and phosphorus in soybean, pea, lentil and effects on nutrient supply and crop yield in the succeeding year in Saskatchewan, *Canadian Journal of Plant Science*, *98*, 5–16.

How to cite this article: Ruis SJ, Blanco-Canqui H, Elmore RW, et al. Impacts of cover crop planting dates on soils after four years. *Agronomy Journal*. 2020;112:1649–1665. https://doi.org/10.1002/agj2.20143