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Abstract

Cover crops (CC) in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotations may prevent N loss and provide other ecosystem services but CC productivity in the western Corn Belt is limited by the short growing season. Our objective was to assess CC treatment and planting practice effects on CC biomass, spring soil nitrate concentrations, and soybean yield at two rainfed sites in eastern

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and one irrigated site in south-central Nebraska over 4 yr. Cover crop treatments (cereal rye [*Secale cereale* L.] [RYE] and a mix of rye, legume, and brassica species [MIX]) were planted by broadcast interseeding into corn stands in September (pre-harvest broadcast) or drilling after corn harvest (post-harvest drilled) and terminated 2 wk before planting soybean. Cover crop biomass and N uptake varied between years, but generally at the eastern sites, pre-harvest broadcasting produced more biomass than post-harvest drilling (1.64 and 0.79 Mg ha^{-1}, respectively) and had greater N uptake (37 and 24 kg ha^{-1}, respectively). At the south-central site, post-harvest drilling produced more than pre-harvest broadcasting (1.44 and 1.20 Mg ha^{-1}, respectively). RYE had more biomass than MIX (1.41 and 1.09 Mg ha^{-1}, respectively), but the same N uptake. Soil nitrate reductions after CC were small. In 3 of 12 site-years, soybean yielded less after pre-harvest CC. Yield reductions were not correlated to CC biomass, but were likely due to greater weed pressure. High CC productivity is necessary for high N uptake, and requires site-specific selection of planting practice and CC treatments.

Abbreviations — CC, cover crops; CON, control without cover crops; MIX, mix of rye, legume, and brassica cover crop species; RYE, cereal rye cover crop.

Core Ideas

- Cover crop (CC) management had site-specific effects on CC productivity, soybean yield.
- Pre-harvest broadcast CC had greater biomass, N uptake in eastern Nebraska.
- Post-harvest drilled CC had greater biomass, N uptake in south-central Nebraska.
- Site, planting practice determined whether RYE had more biomass than a MIX.
- Soybean yield was unaffected by CC in nine, reduced in 3 site-years.

1 Introduction

In the western Corn Belt's prevalent corn–soybean rotations, no crop is grown for approximately 6 mo between corn harvest and soybean planting, increasing the potential for wind and water erosion, nutrient run-off, and leaching. Nitrate leaching from agricultural fields has led to groundwater nitrate concentrations greater than the 10 mg kg^{-1} standard set as safe for human consumption in many areas of the western Corn Belt, including south-central and northeastern Nebraska (Nebraska Department of Environment and Energy, 2019). Cover crops (CC) are promoted to reduce nitrate leaching and erosion potential (USDA, 2019), and can have additional benefits such as suppressing weeds (Osipitan, Dille, Assefa, & Knezevic, 2018). Farmers often report higher soybean yields following CC (SARE, 2017), although CC soil moisture use may have the potential to lead to lower soybean yields in rainfed sites in the western Corn Belt (Williams, Mortensen, & Doran, 2000).

The driver for many functions is aboveground CC biomass. Small grain CC that produced at least 1 Mg ha^{-1} of biomass reduced soil nitrate leaching in Maryland (Hively et al., 2009); 1.1–1.5 Mg ha^{-1} of biomass reduced erosion (USDA, 1999), and 4 Mg ha^{-1} suppressed weeds (Finney, White, & Kaye, 2016). Cover crop biomass quality parameters (N concentration, N uptake, C/N ratio) are indicators of N retention and supply functions in that they determine how fast and how much N will be mineralized from decomposing CC (Finney et al., 2016; Sievers & Cook, 2018; Thapa et al., 2018). Cover crops with low C/N ratios decompose faster, and if coupled with high biomass N content, can supply N to the following crop. High C/N residue decomposes slower, retaining N for longer periods, which may prevent N loss through leaching. In the western Corn Belt, limited access to growing degree days, precipitation and radiation after corn harvest often leads to low CC biomass and N content (Appelgate, Lenssen,Wiedenhoeft, & Kaspar, 2017; Pantoja, Woli, Sawyer, & Barker, 2015), restricting the ability of CC to function as intended.

To overcome these limitations, CC can be broadcast seeded prior to corn harvest by airplane or high clearance equipment into corn stands in late summer (Wilson, Baker, & Allan, 2013). While planting date studies consistently show that CC planted by late September to early October produce more biomass than later planted CC (Duiker, 2014; Farsad, Randhir, Herbert, & Hashemi, 2011); broadcasting onto the soil without incorporation may reduce emergence compared to drilling (Collins & Fowler, 1992; Fisher, Momen, & Kratochvil, 2011; Haramoto, 2019) because of decreased seed-to-soil contact. Several authors have reported on the productivity of aerially seeded CC (Blanco-Canqui, Sindelar, Wortmann, & Kreikemeier, 2017) or post-harvest drilled CC (Ruis, Blanco-Canqui, Jasa, Ferguson, & Slater, 2017; Sindelar, Blanco-Canqui, Jin, & Ferguson, 2019) in Nebraska, but the only studies that specifically compared CC planting dates and methods were from the mid-Atlantic region (Fisher et al., 2011) and upper mid-South (Haramoto, 2019), which have more growing degree days and precipitation than the western Corn Belt. Information on the biomass quantity and quality of a pre-harvest broadcast CC compared to a post-harvest drilled CC can help in making site-specific management decisions for desired CC functions.

Selecting suitable CC species is another important management decision. A common CC species is cereal rye because of its winter hardiness (Fowler, Byrns, & Greer, 2014), biomass production (Duiker, 2014), soil nitrate retention (Blanco-Canqui, 2018), and forage provision (Drewnoski et al., 2018). Farmers also plant leguminous CC, such as hairy vetch (*Vicia villosa* Roth) and winter pea (*Pisum sativum* L.) for N supply, and brassicas, such as forage collards (*Brassica oleracea* L.) and radish (*Raphanus sativus* L.), for N retention (Dean & Weil, 2009) and forage (Drewnoski et al., 2018). Mixes of legume and small grain CC can enhance species diversity in agroecosystems and improve both N retention and N supply services to a subsequent crop (White et al., 2017) due to the complementary functional traits of the species in the mix (Thapa et al., 2018). Surveys showed that half or more of the farmers who grow CC select mixes, often a combination of cereal rye, hairy vetch, and radish (Oliveira, Butts, & Werle, 2019; SARE, 2017); despite higher seed costs and sometimes low productivity (Appelgate et al., 2017; Murrell et al., 2016). Brassicas and legumes have greater growing degree requirements than cereal rye, and mixes including these species may have to be established earlier than cereal rye, for example by pre-harvest broadcasting into corn stands. However, to our knowledge, no studies have compared planting practices for CC mixes in corn–soybean sequences.

The objectives of our study were to evaluate the effects of CC planting practice and CC treatment on (a) CC emergence, biomass production and biomass quality; (b) soil nitrate in the spring; and (c) subsequent soybean yields. We hypothesized that pre-harvest broadcast CC would have lower emergence than post-harvest drill CC; but would have greater biomass, N uptake, C/N ratio, and soil nitrate concentration reductions, and similar subsequent soybean yield than post-harvest drilled CC. We further hypothesized that a CC species mix would have greater emergence, biomass, N uptake and lower C/N ratio than a monoculture CC. When compared to a no CC control, our hypothesis was that both a CC species mix and a CC species monoculture would reduce soil nitrate concentrations, and would not impact soybean yield.

2 Materials and methods

2.1 Site descriptions

Experiments were carried out in 2014/2015, 2015/2016, 2016/2017, and 2017/2018 at three University of Nebraska- Lincoln research farms: the South Central Agricultural Laboratory near Clay Center, the Haskell Agricultural Laboratory near Concord in northeastern Nebraska, and the Eastern Nebraska Research and Extension Center near Mead. Soils at all sites were deep, moderately well drained, without tile drainage, and with a slope of less than 3%. At Clay Center (40◦34′ N, 98°08′ W; altitude 552 m; transition between sub-humid and semi-arid, USDA hardiness zone 5b; 689 mm annual precipitation), soil was a Hastings silt loam (fine, montmorillonitic, mesic Udic Argiustolls). At Concord (42°22′ N, 96°57′ W; altitude 438 m; subhumid, zone 5a; 755 mm annual precipitation), soil was a Baltic silty clay (fine, montmorillonitic, mesic Cumulic Haplaquolls). At Mead (41°09′ N, 96°24′ W; altitude 347 m; subhumid; zone 5b; 768 mm annual precipitation), soil was a Sharpsburg silty clay loam (fine, montmorillonitic, mesic Typic Argiudolls). The Clay Center site was irrigated between June and August, while the Concord and Mead sites were rainfed. Additional information on climate conditions at each site can be found in Barker et al. (2018).

2.2 Experimental design

At each site, CC were planted in one corn field and one soybean field. The corn and soybean crops were rotated between fields from year to year, but the same CC was planted in each experimental unit each fall. In this paper, we report findings only from the soybean year (CC planted into corn and followed by soybean). The experimental design was a randomized complete block design arranged as factorials of CC treatment × planting practice. Blocks were replicated four times at Clay Center and Concord and three times at Mead. The three CC treatments were a monoculture of cereal rye cultivar Elbon (RYE), a species mixture (MIX) of cereal rye, forage radish cultivar Nitro, hairy vetch “variety not stated”, and Austrian winter pea cultivar Whistler; and a control (CON) treatment without CC. The two planting practices were preharvest broadcasting into stands of corn in September and post-harvest drilling after corn harvest. Planting time and planting method were confounded; however, they represent two common CC establishment practices (Oliveira et al., 2019). We will use the term “planting practice” to denote the combination of planting time and associated planting method.

The RYE treatment was planted at 300 pure live seeds m^{-2} each year. In the first and second year, MIX was planted at 150, 20, 10, and 8 seeds m^{-2} for cereal rye, radish, hairy vetch and winter pea, respectively. In the third and fourth year, in an attempt to improve biomass contribution of the non-rye species to MIX biomass, the seeding rates for legumes were doubled and the radish was replaced by forage collard cultivar Impact which has more seeds per kilogram than radish. Years 3 and 4 MIX seeding rate was 150, 160, 20 and 16 seeds m^{-2} for cereal rye, forage collard, hairy vetch and winter pea, respectively. The same seeding rate was used for the preharvest broadcast and post-harvest drill planting practices.

2.3 Plot management

Research plots measured 6 by 12 m at Concord, 6 by 9 m at Clay Center, and 4.5 by 9 m at Mead. All plots were under no-till management with site-specific soybean cultivars, planting dates, and herbicides. The pre-harvest planting was carried out when corn had reached R5.5 stage (“half-milk line”) (Abendroth, Elmore, Boyer, & Marlay, 2011), in September (Table 1). At Clay Center and Mead, seed was broadcast by hand, and at Concord, it was broadcast with a one-row cone seeder fitted with an inflector to spread the seed over the width of the row. The pre-harvest seeding resembles broadcast interseeding with high-clearance equipment where seed is dropped below the top of the corn canopy and is not incorporated into the soil. Corn was harvested between mid-October and late November each year. The post-harvest plots were then planted with a 3P606 No-Till Great Plains drill (Great Plains Inc.) at a depth of 2.5 cm in 0.18 m rows. The following spring, approximately 2 wk before soybean planting, CC were terminated with 0.26 kg a.i. ha^{-1} glyphosate [*N*-(phosphonomethyl)glycine]. Glyphosate-resistant soybean {glufosinate [*RS*-2-Amino- 4(hydroxy(methyl) phosphonoyl)butanoic acid]-resistant at Concord} were no-till planted into the CC residue in 0.76 m rows in late April to mid-May. In the first year, glyphosate (glufosinate at Concord) was used twice for in-season weed control in soybean. Residual herbicides were omitted to avoid herbicide carryover injury to the following CC. In the subsequent years, 0.06 kg a.i. ha^{-1} lactofen Ethyl *O*-[5- (2-chloro-α,α,α-trifluoro-p-tolyloxy)-2-nitrobenzoyl]-DL-lactate (tradename cobra) was added to the in-season spraying regime, to improve weed control. Soybean at Clay Center was irrigated six to seven times between July and August, each time with 3.4 cm of water, applied with an overhead linear irrigation system. Cover crops were never irrigated.

2.4 Measurements

Cover crop plant counts were taken in late October to mid-November, before the first killing freeze, by placing two 0.3 by 1.5 m frames randomly in each plot perpendicular to the length of the plot. Included in the counts were all CC that were at least at growth stage 10 according to the Biologische Bundesanstalt, Bundessortenamt and chemical industry (BBCH) (BBCH, 2001) scale (scale developed for uniform growth staging of all mono- and dicotyledonous plants). Growth stage 10 in cereals describes the first leaf through the coleoptile, in pea is equivalent to the pair of scale leaves visible, and in brassica is the stage where cotyledons are completely unfolded. Cover crops were not counted in 2014/2015 or 2016/2017. In some site-years, post-harvest drilled CC had not reached BBCH stage 10, and thus only pre-harvest CC were counted.

Cover crop biomass in the spring was sampled within 4 d of termination except at Clay Center in 2016/2017 and Concord in 2017/2018 where wet conditions delayed termination (**Table 1**). Using the sampling method described for plant counts, all CC within the two frames were clipped at the soil surface, sorted by species except in 2014/2015, dried at 60 °C to constant weight, and weighed. In all years except 2014/2015, biomass was analyzed for N concentration by elemental combustion analysis on a LECO TruMac Nitrogen/ Carbon Analyzer (LECO Corporation). Species in the MIX were combined and analyzed together for N concentration. Nitrogen uptake was calculated by converting N concentrations to a kg ha^{-1} basis by multiplying with the CC biomass. In 2015/2016 theMIX used for C and N analysis had a slightly

Table 1 Cover crop (CC) and soybean planting, harvest and sampling schedule for all site-years

Activity	*Clay Center*	*Concord*	*Mead*
2014/2015			
Pre-harvest broadcast	18 Sept. 2014	18 Sept. 2014	8 Sept. 2014
Post-harvest drill	21 Oct.	28 Oct.	23 Oct.
CC biomass sampling	30 Apr.	29 Apr.	28 Apr.
Soil nitrate sampling	—	—	—
CC termination	28 Apr.	2 May	29 Apr.
Soybean planting	27 May	18 May	18 May
Soybean harvest	7 Oct.	13 Oct.	9 Oct.
2015/2016			
Pre-harvest broadcast	3 Sept. 2015	10 Sept. 2015	3 Sept. 2015
Post-harvest drill	12 Oct.	16 Oct.	14 Oct.
CC biomass sampling	4 May	5 May	25 Apr.
Soil nitrate sampling	19 May	16 May	4 Apr.
CC termination	5 May	5 May	26 Apr.
Soybean planting	13 May	18 May	2 June
Soybean harvest	10 Oct.	14 Oct.	23 Oct.
2016/2017			
Pre-harvest broadcast	30 Aug. 2016	8 Sept. 2016	6 Sept. 2016
Post-harvest drill	21 Oct.	11 Nov.	11 Nov.
CC biomass sampling	27 Apr.	9 May	2 May
Soil nitrate sampling	27 Apr.	9 May	4 Apr.
CC termination	5 May	9 May	5 May
Soybean planting	12 May	15 May	31 May
Soybean harvest		17 Oct.	8 Nov.
2017/2018			
Pre-harvest broadcast	4 Sept. 2017	8 Sept. 2017	11 Sept. 2017
Post-harvest drill	Late Oct.	8 Nov.	22 Nov.
CC biomass sampling	26 Apr.	9 May	4 May
Soil nitrate sampling	8 May	30 Apr.	4 May
CC termination	24 Apr.	16 May	8 May
Soybean planting	Mid-May	24 May	17 May
Soybean harvest	Mid-Oct.	23 Oct.	24 Oct.

different species composition, in that it contained three additional species (balansa clover [*Trifolium michelianum* Savi], forage collards [*Brassica oleraceae* L.], and black oat [*Avena strigosa* Schreb.]). The additional species winter-killed, and in the spring, biomass of this CC consisted of 99.0% cereal rye.

Soil nitrate was measured each spring by collecting four soil cores to a depth of 0.2 m in each plot. Within one day of sampling, samples were delivered to a commercial laboratory (Ward Laboratories), and soil nitrate was assessed on a Lachat Flow Injection Analyzer (Lachat Instruments). Soybean grain was harvested in October and November (Table 1) with a plot combine from the center two rows of each plot at Clay Center and Concord, and the center three rows at Mead. Grain yield was adjusted to 13% moisture. Soil water content in selected CC treatments was sampled at this site between fall 2014 and spring 2017 and was reported by Barker et al. (2018). Changes in soil physical properties in this experiment were described by Ruis et al. (2020). Daily temperature and rainfall data were obtained from the High Plains Regional Climate Center from stations located at Harvard near Clay Center, Concord, and Mead Agrofarm. Growing degree days for CC were calculated from the daily maximum and minimum temperatures, using a base temperature of 0 °C as recommended by Strand (1987) for small grains in northern regions. Thirty-year normals (1981–2010) from the High Plains Regional Climate Center were obtained from the Clay Center City station for Clay Center, the Haskell Agricultural Laboratory at Concord, and the Mead 6 S station.

2.5 Data analysis

Data were analyzed with the GLIMMIX procedure in SAS 9.4. (SAS Institute). Analysis of variancewas carried out,with the fixed effects of CC species, planting practice, year and site and their interactions, tested over the random effect of the year × site × block interaction. The results of the ANOVA tests for all outcome variables are presented in **Table 2**. Nonsignificant effects were then removed from the model and the LSMEANS statement was used to obtain estimates of the significant effects. For biomass quality, where interactions with year and site were significant, the Slicediff option was used to separate simple effects of planting practice and/or CC species within a given site using pair-wise comparisons at a significance level of $\alpha = .05$. Cover crop fall stand counts were not taken for each planting practice at each site-year because CC had not always reached growth stage 10. Thus the CC fall stand count data was tested across site-years with the fixed effects of species and planting practice and the random effect of year × site × block.

To determine whether rainfall within 7 d after planting (DAP) was a predictor for pre-harvest broadcast CC fall stand counts, the sum of rainfall within 7 DAP was used as a fixed factor in GLIMMIX and the interaction of year × site × rep as random factor.We were also interested in whether the amount of CC biomass affected soybean yield.

Table 2 Source of variation, degrees of freedom (df), and significance levels for CC spring biomass (biomass), biomass N concentration (%N), biomass N content (Total N), biomass C/N ratio (C/N), soil nitrate concentration (NO3–N), and soybean grain yield following CC (Yield). Degrees of freedom vary, because not all years and treatments were included in each analysis of variance

Sources of variation	*df*	*Biomass*	*df*	*%N*	*Total N*	*C/N*	*df*	*NO_3-N*	*df*	*Yield*
Site (S)	2	<0.0001	2	<0.0001	<0.0001	<0.0001	2	<0.0001	2	<0.0001
Year (Y)	3	<0.0001	2	<0.0001	<0.0001	<0.0001	2	<0.0001	3	<0.0001
Y ×S	6	<0.0001	4	<0.0001	0.0006	<0.0001	4	<0.0001	6	<0.0001
Planting practice (P)	1	<0.0001	1	<0.0001	0.0050	<0.0001	1	0.0006	1	0.0040
S ×P	2	<0.0001	2	<0.0001	<0.0001	<0.0001	2	<0.0001	2	0.3969
Y × P	3	<0.0001	2	0.0002	<0.0001	0.7316	2	<0.0001	3	0.6928
Y × S ×P	6	<0.0001	4	0.0048	<0.0001	<0.0001	4	<0.0001	6	0.0327
CC treatment (T)	1	<0.0001	1	0.0042	0.7069	<0.0001	2	<0.0001	2	0.3806
S × T	2	0.0284	2	0.2895	0.0123	0.0088	4	<0.0001	4	0.2413
Y × T	3	0.1294	2	0.7671	0.7331	0.0002	4	<0.0001	6	0.7436
Y × S × T	6	0.6435	4	0.6373	0.4505	0.0333	8	<0.0001	12	0.6033
T × P	1	0.2061	1	0.1518	0.6935	0.6089	2	0.1096	2	0.1161
S × T × P	2	0.0024	2	0.2175	0.2816	0.1245	4	0.0007	4	0.9147
Y × T × P	3	0.9981	2	0.0213	0.4047	0.0489	4	0.0001	6	0.9244
Y × S × T × P	6	0.6299	4	0.7355	0.5055	0.8365	8	<0.0001	12	0.8479

Biomass depends on CC treatment and planting time, thus biomass was included as a linear covariate. The regression model for soybean yield thus had as fixed effects the significant effects (site × year × planting practice) and the linear covariate CC biomass. Random effects were the year × site × rep interaction. Where the models were significant, we used the GLM procedure to fit a linear and a quadratic model to the data. The model with the greatest coefficient of determination (R^2) was selected as the best fit.

3 Results and discussion

3.1 Weather

Monthly temperatures and precipitation are shown for Clay Center in **Figure 1,** for Concord in **Figure 2**, and for Mead in **Figure 3**. We discuss deviations from normal if they are greater than 10% for temperature and 20% for precipitation. In the first year (2014/2015), temperatures during the CC growing period (September–April) were close to the 30-yr normal, except for November, when daily temperatures dropped to −5 to −10 °C for about 10 d. February was 3–4 °C colder than normal, and March was 2–3 °C warmer than normal. In the second year (2015/2016), September through April (with the exception of January) monthly temperatures at all sites were 2–4 °C warmer than normal, including several 10 °C d between mid-February and mid-March. April rainfall was 70, 80, and 50 mm more than normal at Clay Center, Concord, and Mead, respectively. In the third year (2016/2017), October, November, and March temperatures at all sites were 2–3 °C above normal. February temperatures were 3–5 °C warmer at Clay Center and Concord. Total rainfall during the CC growing period was normal, except in the fall at Mead, where rainfall was 49 mm less than normal. In 2017/2018, temperatures during the fall were near normal, but February was 3–4 °C colder, and April was 4 °C colder. In April, only 14, 27, and 6 mm of rain fell at Clay Center, Concord, and Mead, respectively.

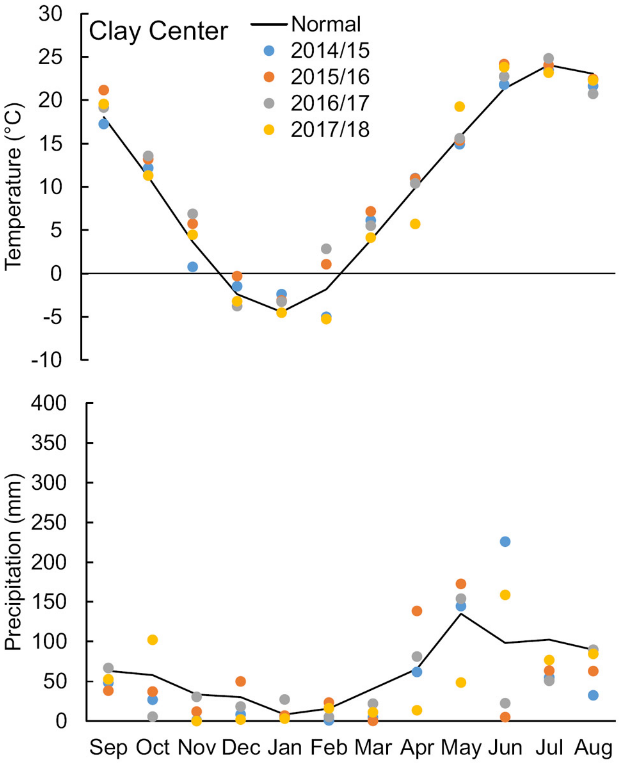

Figure 1 (top) Mean monthly temperature and (bottom) precipitation for the Clay Center site for each year of the study. Long-term (1981–2010) average temperature and precipitation are shown as black lines. This site was irrigated in July and August but irrigation is not included in precipitation.

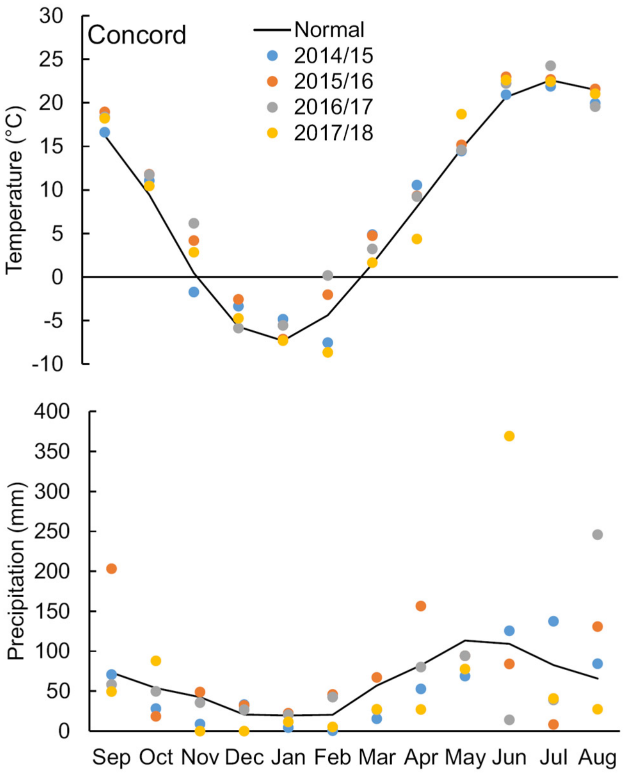

Figure 2 (top) Mean monthly temperature and (bottom) precipitation for the Concord site for each year of the study. Long-term (1981–2010) average temperature and precipitation are shown as black lines.

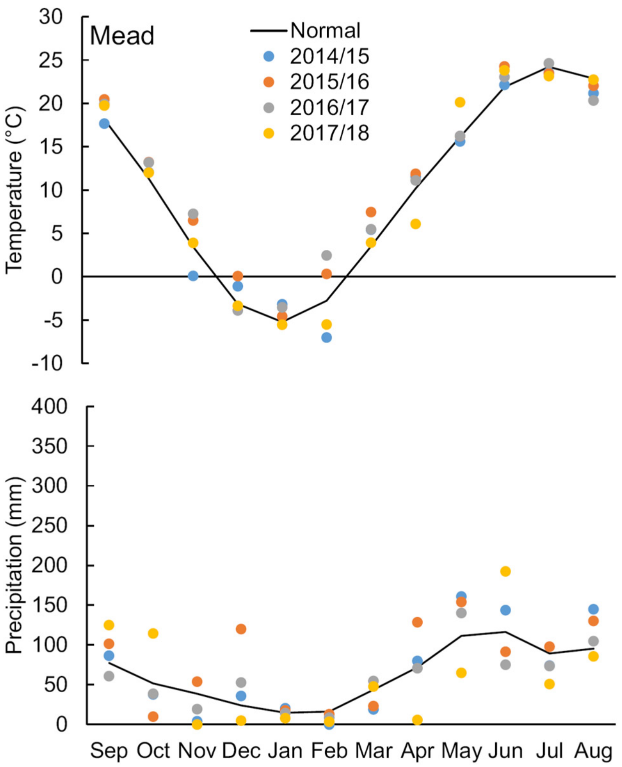

Figure 3 (top) Mean monthly temperature and (bottom) precipitation for the Mead site for each year of the study. Long-term (1981–2010) average temperature and precipitation are shown as black lines.

3.2 Cover crop emergence

Cover crop treatment and planting practice interactions influenced fall stand counts (*P* = .022) (data not shown). The RYE treatment had higher stand counts when it was drilled post-harvest than when it was broadcast pre-harvest (125 and 64 plants m^{-2}, respectively). The stand counts of the MIX treatment did not differ with planting practice, and were 62 plants m^{-2} in the post-harvest drill and 78 plants m^{-2} in the pre-harvest broadcast planting. The MIX treatment did not have higher stand counts when drilled post-harvest, probably because brassicas, hairy vetch, and winter pea often had not yet reached growth stage 10 and were not included in the counts. Thus, MIX counts likely represent the cereal rye portion of the CC, which was 50% of the seeding rate of RYE (150 seeds m^{-2} and 300 seeds m^{-2}, respectively). Due to their greater temperature needs for germination and emergence, brassica and legume plants may not be suitable for establishment post-harvest corn in Nebraska.

Few studies compared drilled and broadcast RYE fall plant densities (Fisher et al., 2011; Haramoto, 2019). They found that drilled RYE has higher plant densities in the fall because drilling increases seed-soil contact and thus moisture available to seeds to imbibe water, germinate, and emerge. These studies established CC at the same time, after corn harvest, whereas in our study, the broadcast CC were planted 6–8 wk earlier than the drilled CC, into standing corn. Although the potential for growing degree accumulation was greater in the pre-harvest planting, shading by the corn may have reduced CC seedling survival as reported by Belfry and Van Eerd (2016) and Noland et al. (2018). Colder and drier fall weather may be another reason why our CC plant densities were lower than those reported by Haramoto (2019) in Kentucky. For the greatest productivity of broadcast CC, rainfall within a week after planting is important (Wilson et al., 2013), and broadcast CC often take weeks to emerge depending on rainfall frequency (Fisher et al., 2011). In our trials in the fall, the pre-harvest CC growth stages (according to the BBCH scale) ranged from 10 to 29, probably because these seedlings emerged over a longer period.

To determine whether rainfall within 7 DAP contributes to greater emergence of pre-harvest broadcast planted CC, we carried out a regression analysis. We used rainfall as predictor variable in the model, but not CC treatment since preharvest broadcast RYE and MIX had

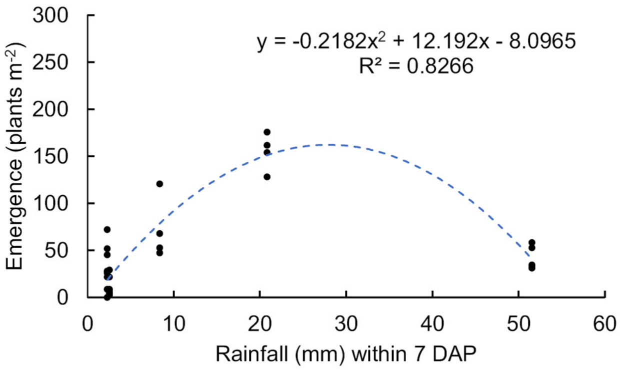

Figure 4 Pre-harvest broadcast cover crop emergence in plants m^{-2} as affected by total rainfall in millimeters within 7 days after planting (DAP). Five of 12 site-years were included in the regression, because emergence data were not available from all site-years.

the same emergence (P = .4885, data not shown). Rainfall within 7 DAP had a significant effect (P < .0001) (**Figure 4**) and this relationship was best described with the quadratic model (R^2 = .83). Cover crop emergence increased with increasing amounts of rainfall within 7 DAP, peaked at 28 mm of rainfall within 7 DAP, and then decreased. The decline in emergence may have been caused by heavy rainfall that washes out seeds. Such an event occurred only once in our study, and this outlier could have skewed the analysis due to the relatively small sample size. Including more site-years in this analysis would capture more of the variability in fall precipitation in Nebraska (Figures 1, 2, and 3), leading to better understanding of how the amount of rainfall affects CC emergence.

3.3 Cover crop biomass production

Cover crop biomass production was influenced by the effect of site-year and its interactions with CC treatment and planting practice. We discuss site-year effects first, and then the interactions with CC treatment and planting practice. In our study, site-years that had awarmandwet growing seasonwere most beneficial to CC biomass production, but occurred only in 2015/2016 at all sites. In that year, mean CC biomass across treatments, planting practices and sites, was 2.66 Mg ha^{-1}. Most other site-years were warmer, but drier than the

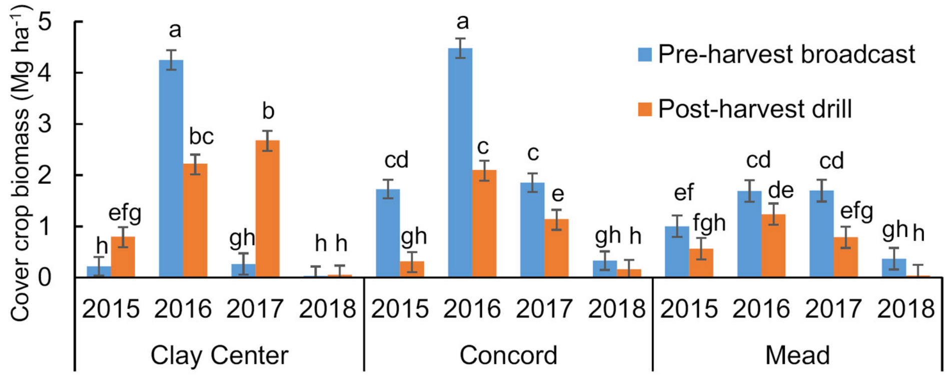

Figure 5 Cover crop biomass in the spring as affected by the site-year and planting practice interaction, averaged across CC treatment. Blue bars denote pre-harvest broadcast planting and red bars post-harvest drill planting. Lines above bars indicate standard errors. Bars with the same letter are not significantly different from each other.

norm. The year 2017/2018 was colder and drier at all sites and was most detrimental to CC biomass production with mean CC biomass of only 0.16 Mg ha^{-1}. No site-years were colder and wetter than the 30-yr average

The effect of CC planting practice differed with site-years (Table 2, Figure 5). At Concord broadcasting pre-harvest was the more productive planting practice, with twice the amount of biomass as the post-harvest drilling, likely because it accumulated twice the growing degree days as post-harvest drilling (**Table 3**). At Mead, pre-harvest broadcast planting increased productivity only in 2016/2017, with no differences between planting practices in the other years, although the pre-harvest broadcasting tended to have greater biomass. Average pre-harvest broadcast biomass was 2.10 Mg ha^{-1} at Concord and 1.19 Mg ha^{-1} at Mead. In 2015/2016 preharvest broadcast CC biomass was 4.48 Mg ha^{-1} at Concord, 2.79 Mg ha^{-1} more than the pre-harvest planting at Mead. At Concord, three times the normal amount of rain fell in September of that year, likely increasing emergence of preharvest broadcast CC at this site (Fisher et al., 2011; Wilson et al., 2013). Concord and Mead average post-harvest drill biomass was 0.66 and 0.93 Mg ha^{-1} respectively, similar to other studies in eastern Nebraska where CC were drill planted after corn harvest (Kessavalou & Walters, 1997; Ruis et al., 2017).

Table 3 Growing degree day accumulation in °C (base temperature 0 °C) for pre-harvest broadcast and post-harvest drilled CC from planting to spring biomass sampling

Planting practice	*Growing degree days*		
	Clay Center	*Concord*	*Mead*
		°C	
2014/2015			
Pre-harvest broadcast	1417	1239	1520
Post-harvest drill	923	669	852
2015/2016			
Pre-harvest broadcast	1941	1480	1865
Post-harvest drill	1201	910	1102
2016/2017			
Pre-harvest broadcast	1911	1625	1820
Post-harvest drill	1028	737	799
2017/2018			
Pre-harvest broadcast	1402	1312	1415
Post-harvest drill 559[a]	541	564	

a. Assume planting date of 25 October because actual planting date was not available.

At Clay Center, the post-harvest planting generally produced more biomass than the pre-harvest planting. Precipitation during September, October, and November during the course of this study was on average 20 mm per month less at Clay Center than at the other sites, which may have reduced the emergence of broadcast planted CC (Wilson et al., 2013). This site accumulated 100–200 more growing degree days in the post-harvest planting than the other sites (Table 3), due to warmer weather and earlier planting, resulting in greater post-harvest planting productivity. Blanco-Canqui et al. (2017) drill-planted cereal rye into a continuous corn cropping sequence at the same site and when terminated at the end of April, CC productivity was similar to our study with 1.5 Mg ha^{-1} in 2014/2015 and 3.7 Mg ha^{-1} in 2015/2016. The only year when the pre-harvest broadcast planting at Clay Center produced more than the post-harvest drill was 2015/2016, likely because of the mild winter and unusually warm and wet spring which probably resulted in an advantage for pre-harvest broadcast CC. The very cold and dry spring of 2017/2018 resulted in very low biomass at Clay Center and the other sites. Cover crops were observed to be in growth stages 13–22 (beginning tillering; BBCH, 2001) whereas in the other years, they were in growth stages 30–45 (stem elongation to booting).

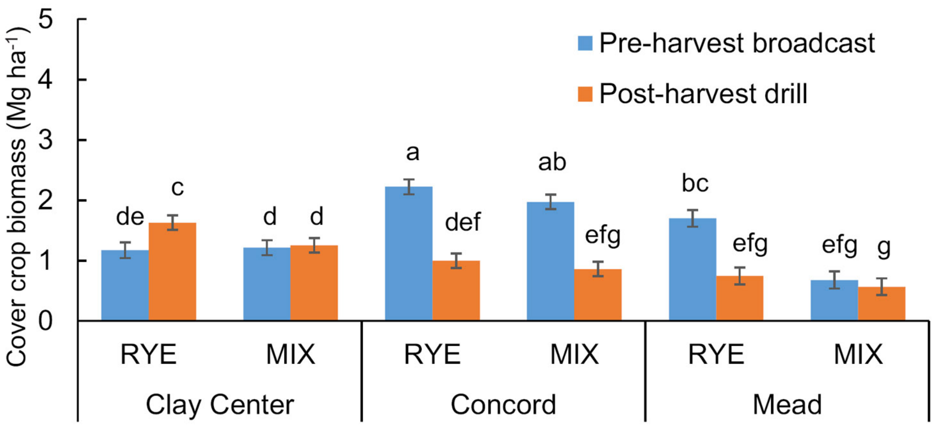

Figure 6 Cover crop biomass in the spring as affected by the site × CC treatment × planting practice interaction, averaged over 4 yr. Blue bars denote pre-harvest broadcast planting and red bars post-harvest drill planting. Cover crops were RYE (cereal rye) or MIX (combination of cereal rye, hairy vetch, winter pea, and forage radish). Lines above bars indicate standard errors. Bars with the same letter are not significantly different from each other.

The RYE treatment produced more biomass than the MIX treatment (1.41 and 1.10 Mg ha^{-1}, respectively) when averaged across all variables. Cover crop treatment interacted with site and planting practice (Table 2, **Figure 6**). At Clay Center in the post-harvest drill planting, RYE produced 39% more biomass than MIX, however, in the pre-harvest broadcast planting, RYE and MIX performed the same. At Concord, only planting practice was a factor, with no difference in productivity between RYE and MIX in either planting. The pre-harvest broadcast planting of RYE at Mead had 128% or 0.95 Mg ha^{-1} more biomass than the MIX pre-harvest drill planting, but both treatments produced the same in the post-harvest drill planting. Cereal rye made up 80% of the total seeds in the MIX treatment and in the spring, on average 90% of the total mix biomass was rye (data not shown) with the remainder comprised of hairy vetch and winter pea, because the brassicas winterkilled. Predominance of cereals when grown with non-grass species is common (Appelgate et al., 2017, Murrell et al., 2016), even when the frequency of cereal rye seed m^{-2} is less than that of the other species (Poffenbarger et al., 2015). Cereal rye has a competitive advantage because it is more cold-hardy than the legumes and resumes growth earlier in the spring. To increase the productivity of other species, it may be necessary to give them a competitive advantage by planting them earlier than cereal rye (Hayden, Ngouajio, & Brainard, 2015).

The critical planting date for cereal rye based on growing degree accumulation is the third week of September in zone 5 (Farsad et al., 2011).With pre-harvest broadcast planting, we were able to establish CC before the critical planting date, capturing more growing degree days (Table 3), which is important in cooler sites. The trade-off for broadcast planting is lower plant counts, but low cereal rye populations in the fall are not necessarily an indicator of decreased spring biomass, as cereal rye can compensate for low populations by increased tillering (Peltonen-Sainio, Rajala, & Muurinen, 2002). There is also evidence that the cereal rye in MIX compensated for low populations compared to rye alone. The cereal rye seeding rate in MIX was 150 seeds m^{-2} and in RYE 300 seeds m^{-2}, yet the cereal rye biomass in MIX was 70% of the cereal rye biomass in RYE (0.99 and 1.41 Mg ha^{-1}, respectively). Planting cereal rye at the lower seeding rate could save farmers costs compared to planting RYE or MIX, especially in the post-harvest broadcast planting as both treatments had similar biomass.

The amount of CC biomass is closely related to several CC functions (Finney et al., 2016). Cover crops reached the threshold for reducing soil nitrate concentrations (1.0 Mg ha^{-1}) (Hively et al., 2009) in most years when planting pre-harvest at the eastern sites and post-harvest at Clay Center. The threshold for weed suppression (4.0 Mg ha^{-1}, Finney et al., 2016) was reached in only 2 site-years. To increase CC biomass production, the CC growing season in the spring can be extended, for example Duiker (2014) found that mid-October planted CC produced approximately 0.5 Mg ha^{-1} in early May, approximately 1.0 to 2.0 Mg ha^{-1} by mid-May, and 2.0 to 3.3 Mg ha^{-1} by early June. However, delaying CC termination delays soybean planting. Alternatively, the CC growing season could be extended by planting CC earlier after corn hybrids with shorter relative maturities or by interseeding CC into corn at V7 with a high-clearance no-till drill (Noland et al., 2018), irrigating CC in drier areas to improve emergence (Ruis et al., 2019), selecting a cultivar with high biomass potential such as cultivar Elbon (Kaspar & Bakken, 2015), or terminating the CC after soybean has been planted (Reed, Karsten, Curran, Tooker, & Duiker, 2019). These alternative methods of CC management deserve further research.

3.4 Cover crop biomass quality

Cover crop biomass quality variables (biomass N concentration inmg kg^{-1}, biomassNuptake, and biomass C/N ratio) are dependent and will be discussed as they relate to CC biomass N uptake (total N in biomass on kg ha^{-1} basis). For N uptake, the interaction of site year × planting practice and site × CC treatment were significant (Table 2) and are shown in **Table 4**. Biomass N concentration and C/N were also impacted by the site year × planting practice interactions (Table 2), but only C/N was affected by the site × CC treatment interaction (Table 4). Biomass N concentration was impacted by themain effect of CC treatment, but the site × CC treatment interaction is shown for consistency (Table 4). Where other interactions impacted biomass N concentration and C/N ratio, they are discussed in the text.

Pre-harvest broadcast planting increased N uptake at Concord in 2015/2016 and 2016/2017, and at Clay Center in 2015/2016. Post-harvest drill planting increased N uptake at Clay Center in 2016/2017.

Table 4 Cover crop biomass quality (N concentration in %N, N uptake in kg ha−1, and C/N ratio) for the interaction effects of site-year by planting practice (pre-harvest broadcast and post-harvest drilled) and site by CC treatment (RYE, cereal rye; MIX, combination of cereal rye, hairy vetch, winter pea, and forage radish). Biomass quality was not tested in 2014/2015. In each column, within main effects of planting practice or CC treatment, means followed by the same letter are not significantly different at α = .05.

	Cover crop biomass quality								
	Clay Center			*Concord*			*Mead*		
Factors	*N %*	*N kg ha^{-1}*	*C:N*	*N %*	*N kg ha^{-1}*	*C/N*	*N %*	*N kg ha^{-1}*	*C/N*
Planting practice									
2015/2016									
Pre-harvest broadcast	1.8d	77a	26a	2.2d	102a	19a	1.7d	26ab	26b
Post-harvest drill	1.6d	35c	27a	2.7cd	56b	16a	2.3c	29a	21c
2016/2017									
Pre-harvest broadcast	3.7b	15d	11c	2.6cd	49b	16a	1.4d	20ab	30a
Post-harvest drill	2.5c	67b	17b	2.8c	32c	16a	2.9b	20ab	15de
2017/2018									
Pre-harvest broadcast	5.5a	3d	7c	3.7b	11d	11b	3.0b	11bc	13e
Post-harvest drill	5.8a	2d	7c	4.6a	6d	9b	4.7a	1c	8f
CC treatment									
MIX	3.7a	38a	18a	3.1a	41a	15a	2.8a	14a	21a
RYE	3.3b	29b	14b	3.1a	45a	14a	2.5b	22a	17b

Planting practice had no effect at Mead in any year, or at Clay Center and Concord in 2017/2018. Biomass N uptake is a function of biomass production and biomass N concentration. Planting practices that increased biomass production, such as pre-harvest broadcast planting at Concord in 2015/2016 and 2016/2017, the 2015/2016 pre-harvest planting at Clay Center, and the 2016/2017 post-harvest planting at Clay Center, resulted in greater N uptake. The maximum of 102 kg N ha^{-1} was obtained at Concord in 2015/2016, coinciding with the peak biomass. On the other hand, the more productive plantings had lower biomass N concentrations in 2 site-years, Clay Center in 2016/2017 and Mead in 2016/2017. Biomass N concentrations decrease with advances in growth stages of the plant. Pre-harvest planting established CC approximately 50 d earlier than the post-harvest planting practice (Table 1), but only at Mead did pre-harvest planting consistently result in decreased biomass N concentrations. At Clay Center in 2016/2017, N concentration was greater in the pre-harvest planting. The CC population in the pre-harvest planting was reduced which could have resulted in greater N uptake per plant even if totalNuptakewas less. However, greater productivity of the post-harvest planting practice offset the decline in N concentrations. At Mead in 2016/2017 the pre-harvest planting approximately doubled productivity, but decreased by half the biomass N concentration leading to identical N uptake for both planting practices. Very low N uptake in 2017/2018 coupled with high biomass N concentrations reflects the delay in growth and decline in productivity CC experienced at all sites in that spring. Site effects may have been due to differences in soil fertility and residual N left after corn harvest but fall soil N was not measured. Mean N uptake in the post-harvest planting across all sites was 28 kg ha^{-1}, similar to findings by Pantoja et al. (2015) who tested postharvest drilled RYE in a corn–soybean rotation in Iowa.

The MIX treatment took up the same amount of N as RYE at Concord and Mead, but took up more N than RYE at Clay Center (Table 4). Cover crop mixes of cereal rye and legumes typically have greater N concentrations than cereal rye because the legumes fix atmospheric N (Thapa et al., 2018). This occurred at Clay Center and Mead, probably because they had greater proportions of legumes in MIX biomass than Concord (13, 15, and 3%, respectively, data not shown). However, due to the overall low biomass of the legume component in MIX, we do not expect significant contributions to the biomass N uptake. Another explanation for the higher MIX N uptake may be that MIX had greater access to soil nitrate than RYE. MIX was planted at a lower seeding rate and likely experienced less intraspecific competition than RYE (Brennan, Boyd, & Smith, 2013, Thapa et al., 2018).

Where the planting practice increased N concentration, biomass C/N ratio decreased and vice versa. At Mead, C/N ratio was always greater in the pre-harvest broadcast planting, at Concord it was similar, and at Clay Center, it was greater in the post-harvest drill planting in the year with lower N concentration. The MIX biomass had lower C/N ratios than RYE biomass at Clay Center and Mead, but was not different at Concord. In our study, in 2015/2016 and 2016/2017 the relatively high N uptake at Clay Center and Concord shows CC potential as a tool to reduce soil N and possibly decrease N leaching in the spring before soybean is planted. The N removed by CC is bound in organic form in CC residue, and released once residue is mineralized.

Biomass C/N ratio is a driver of decomposition and N release (Sievers & Cook, 2018), and can be used to predict N retention vs. N release from decomposing CC. In CC decomposition studies in no-till systems, CC residue with high C/N ratios (above 30:1) initially immobilized N, retained N over a longer period of time, and did not release all N within one growing season whereas low C/N ratios released most N within 4 to 6 wk of termination, serving as an N source for the next crop (Ruffo & Bollero, 2003; Sievers & Cook, 2018). In our study, even in site-years with high CC productivity and N uptake such as at Clay Center and Concord in 2015/2016 and 2016/2017, CC biomass N concentrations were relatively high, resulting in C/N ratios that were generally less than 30:1 (Table 4), which likely led to a gradual release of N.More persistent residue, that is, residue with a higher C/N ratio may be desirable in sites where CC are utilized to take up soil N to prevent groundwater nitrate contamination or where CC are grown to provide early season weed control (Osipitan et al., 2018). For these purposes, pre-harvest broadcasting CC and selecting a pure cereal rye over a CC mixture may be the most appropriate management practices. Soybean is a suitable succeeding crop for these situations, as it is not likely to be affected by N immobilization from CC residue.

3.5 Soil nitrate concentration in spring

Planting practice, CC treatment, site, year, and all interactions influenced soil nitrate concentration, except the planting practice by CC treatment interaction (Table 2), but the differences were generally small (2–4 mg kg^{-1}) because soil nitrate levels were low, between 1–5 mg kg^{-1} in most site-years (**Table 5**). In 2015/2016, high CC productivity and N uptake did not lead to reduced soil nitrate concentrations in RYE or MIX compared to CON except at Mead, where CON nitrate concentrations were 5 mg kg^{-1}, 4 mg kg^{-1} more than RYE. Soils were sampled prior to or after biomass sampling (Table 1) due to weather

Table 5 Soil nitrate (mg kg−1) concentrations in the spring for the interaction effects of site-year by planting practice (pre-harvest broadcast and post-harvest drilled) and site-year by CC treatment (RYE, cereal rye; MIX, combination of cereal rye, hairy vetch, winter pea, and forage radish; CON, control with no CC). Soil nitrate was not tested in 2014/2015. In each column, within main effects of planting practice or CC treatment, means followed by the same letter are not significantly different at α = .05.

Factors	*Soil nitrate concentrations*		
	Clay Center	*Concord*	*Mead*
		mg kg^{-1}	
Planting practice			
2015/2016			
Pre-harvest broadcast	3e	3a	3b
Post-harvest drill	3e	3a	4ab
2016/2017			
Pre-harvest broadcast	18a	3a	3b
Post-harvest drill	8d	3a	4ab
2017/2018			
Pre-harvest broadcast	13b	3a	3b
Post-harvest drill	11c	3a	5a
CC treatment			
2015/2016			
RYE	2f	3ab	1b
MIX	2f	3ab	3ab
CON	4e	3ab	5a
2016/2017			
RYE	11 cd	2b	3ab
MIX	9d	2b	4a
CON	19a	4a	4ab
2017/2018			
RYE	9d	2b	4ab
MIX	13b	4a	5a
CON	13bc	4a	4a

conditions that either delayed CC termination or delayed soil sampling and this may have diluted the CC effects. At Clay Center and Concord, where RYE and MIX took up 51–81 kg N ha^{-1}, we expected to see lower soil nitrate concentrations in RYE and MIX than in CON. Although RYE and MIX had just 2–4 mg nitrate kg^{-1}, CON nitrate levels were similarly low. Extreme weather events, such as the heavy rain fall that occurred in April and May (Figures 1 and 2) could have increased nitrate leaching, resulting in low levels in CON plots (Iqbal et al., 2018). The largest treatment differences in soil nitrate concentrations were measured at Clay Center in 2016/2017, where the post-harvest planting reduced soil nitrate by 10 mg kg^{-1} compared to the pre-harvest planting, and RYE and MIX reduced soil nitrate by 10 and 8 mg kg^{-1}, respectively, compared to CON. Interestingly, at that site, despite very low biomass production in 2017/2018, RYE reduced soil nitrate by 4 mg kg^{-1}. The lack of precipitation during the spring could have led to an accumulation of nitrate in CON plots. At Concord, despite reaching the threshold biomass for soil nitrate reduction (Hively et al., 2009), CC did not affect soil nitrate concentrations. Mineralization rates may have been lower at Concord which is on average 2 °C colder than Clay Center in March and April. Soil nitrate sampling during the crop growing season following CC, sampling from deeper in the soil profile, and measuring nitrate leaching losses would more accurately determine the seasonal effects of CC on soil nitrate.

3.6 Soybean yield

The site-year and planting practice interaction affected soybean yield, but CC treatment or its interactions did not (Table 2). Pre-harvest broadcast CC reduced soybean yields in 3 of 12 site-years. At Concord in 2015/2016, soybean after the pre-harvest broadcast CC yielded 0.41 Mg ha^{-1} less than soybean after the post-harvest planting, a 9% decrease (**Table 6**). At Clay Center in 2017, soybean after pre-harvest broadcast CC yielded 0.68 Mg ha^{-1} or 16% less than in post-harvest drilled CC, the largest yield decline measured in our study. Pre-harvest broadcast CC also reduced soybean yield at Concord in 2017/2018, although overall yield at this site was very low. Soybean yield was never higher after CC.

Several factors likely contributed to the yield decrease after pre-harvest planted CC. At Clay Center in 2017 weed pressure was high,

Table 6 Soybean grain yield in Mg ha−1 after a CC, for the interaction effects of site-year by planting practice (pre-harvest broadcast and post-harvest drilled) and site-year by CC treatment (RYE, cereal rye; MIX, combination of cereal rye, hairy vetch, winter pea, and forage radish; CON, control with no CC). In each column, within main effects of planting practice or CC treatment, means followed by the same letter are not significantly different at α = .05.

Factors	*Soybean grain yield*		
	Clay Center	*Concord*	*Mead*
		Mg ha^{-1}	
Planting practice			
2014/2015			
Pre-harvest broadcast	5.39a	4.73ab	4.62a
Post-harvest drill	5.32a	4.97a	4.75a
2015/2016			
Pre-harvest broadcast	5.16a	4.36b	4.42ab
Post-harvest drill	5.15a	4.77a	4.45ab
2016/2017			
Pre-harvest broadcast	3.48c	4.51ab	4.47ab
Post-harvest drill	4.17b	4.57ab	4.58a
2017/2018			
Pre-harvest broadcast	5.57a	2.19d	3.61c
Post-harvest drill	5.36a	2.56c	3.99bc
CC treatment			
2014/2015			
RYE	5.38a	4.81a	4.66a
MIX	5.46a	4.89a	4.56ab
CON	5.22a	4.85a	4.83a
2015/2016			
RYE	4.96a	4.49a	4.34abc
MIX	5.25a	4.63a	4.42abc
CON	5.25a	4.57a	4.55ab
2016/2017			
RYE	3.89bc	4.61a	4.39abc
MIX	3.54c	4.60a	4.64ab
CON	4.05b	4.41a	4.54ab
2017/2018			
RYE	5.48a	2.68bc	3.84d
MIX	5.38a	2.40b	3.58cd
CON	5.54a	2.04c	3.98bcd

because our chemical weed control program did not contain herbicides with a residual to minimize risk of reduced emergence and growth of CC that would be planted in the fall. While all plots had lower yields than in the other years at this site, the difference was most pronounced in the pre-harvest broadcast plantings, which had less CC biomass to suppress weeds than the post-harvest plantings (Figure

5). Inadequate chemical weed control and low CC biomass also likely caused low yields at Concord in 2018. Cover crop weed suppression depends on CC biomass production, for example, CC with at least 4.0 Mg ha^{-1} biomass suppressed weeds almost completely before termination (Finney et al., 2016) and high biomass was also essential to weed suppression during the first 7 wk of crop establishment (Osipitan et al., 2018). Thus managing for high CC productivity, for example by planting pre-harvest, drill planting post-harvest at drier sites, and selecting highly productive species is imperative if chemical weed control applications will be restricted.

The yield reduction at Concord occurred in the year with the highest CC biomass production (in the pre-harvest planting, Figure 5). High amounts of CC residue at planting can interfere with the planting equipment and reduced soybean emergence and subsequently yields in a study in eastern Nebraska (Williams et al., 2000). Soil water deficits left by the CC may have also contributed to lower yields. Barker et al. (2018) measured water content under CON and a sevenspecies CC mixture in our experiment, and found a 10 mm soil water difference between the pre-harvest planting and post-harvest planting in the 0–0.3 m soil depth at Concord in May 2016. This was not a significant difference, however the diverse CC they monitored was not as productive as the RYE and MIX treatments so the actual soil water difference was likely higher. Water stress for soybean in pre-harvest planting may have been increased by the almost complete lack of precipitation in July 2016. April, May, and June have the highest precipitation at our sites, and likely replenish soil water deficits left by a CC. However, in dry years, soil water availability after CC may limit soybean yields. Water deficits during July and August explained most of the variation in soybean yields in northeastern Nebraska under rainfed conditions (Grassini et al,, 2015). Access to irrigation could be the deciding factor for more wide-spread adoption of CC in the western Corn Belt. To determine whether CC biomass was causing soybean yield reductions, we conducted a regression with CC biomass as a covariate in the model. We found no relationship whether the covariate was used in the interaction with site-year (P = .5889), site (P = .7739), year (P = .4575) or by itself (P = .5552) (data not shown). Thus, it is unlikely high CC biomass reduced soybean yields in our study but rather indirect factors, such as compromised weed control, were causing yield losses.

Finally, our pre-harvest planting method may have inadvertently contributed to lower yields, although this was likely a minor factor. Each September when soybean was at R5–R7 (Pedersen, 2014), the CC for the following season was planted by hand by walking through all pre-harvest plots including CON (no seed was spread there). The soybean canopy at this growth stage tended to be tangled and walking through may have broken off some branches and pods.

In short-term research trials, soybean yields were seldom affected by preceding CC (Acuña & Villamil, 2014; Dozier, Behnke, Davis, Nafziger, & Villamil, 2017; Ruffo, Bullock, & Bollero, 2004), however, long-term CC trials often report improvements in soil properties such as aggregate stability and organic matter concentrations (Blanco-Canqui & Jasa, 2019) and soil water storage (Basche et al., 2016) which may lead to higher soybean yields. The relationship of CC productivity, the years a field has been in CC, and subsequent soybean yields needs to be further explored.

4 Conclusion

This study evaluated CC planting practices and treatments on CC biomass production and quality, soil nitrate concentrations, and subsequent soybean yields at three sites in Nebraska. As expected, pre-harvest broadcast CC had lower emergence than post-harvest drilled CC. Our hypothesis that broadcast planting CC pre-harvest results in greater biomass than drilling CC post-harvest was validated for the two eastern Nebraska sites, but not for the south-central Nebraska site, likely due to differences in rainfall distribution and the length of the growing season. We expected pre-harvest broadcast planted CC to have lower biomass quality, but this was only confirmed at one eastern site. Our assumption that the CCmix would have greater biomass production, biomass quality, and N uptake could also not be confirmed, except for greater N uptake at the south-central site. Greater contribution of the non-grass species to the CC mix biomass may improve its biomass quality, but will require adjustments to species composition and planting times. We hypothesized that soil nitrate concentrations would be lower in the pre-harvest, broadcast planting, but this was validated only at the south-central site in 1 yr. In most site-years, CC treatment and planting practice had minor impacts on soil nitrate. Increasing CC biomass production could increase N uptake and N retention, possibly reducing the risk for N leaching although this needs to be verified in the field.We did not expect a yield decrease in soybean due to CC planting practice or treatment, but soybean yield was lower after the pre-harvest planting in 3 of 12 site-years. Secondary weed infestations due to a restrictive herbicide program, and lack of precipitation in 1 yr may have contributed to the yield decrease.

This research demonstrated the need for site-specific CC management to achieve high biomass production, N uptake, and associated environmental benefits. Research should focus on regionally adapted agronomic CC management in order for CC to attain their intended goals.

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Conflicts of interest — The authors declare there are no conflicts of interest.

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