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Cover crop planting practices determine their performance in the U.S. Corn Belt

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Abstract

Cover crop growing periods in the western U.S. Corn Belt could be extended by planting earlier. We evaluated both pre-harvest broadcast interseeding and post-harvest drilling of the following cover crops: (a) cereal rye (*Secale cereale* L.) [RYE]; (b) a mix of rye + legumes + brassicas [MIX1], (c) a mix of rye + oat [*Avena sativa* L.] + legumes + brassicas (MIX2), (d) legumes [LEGU]) and (e) a no cover crop control. These were tested in continuous corn (*Zea mays* L.) [corn–corn] and soybean [*Glycine max* (L.) Merr.]–corn systems [soybean–corn] at three sites in Nebraska for their effect on cover crop productivity, soil nutrients, and subsequent corn performance. At the sites with wet fall weather, pre-harvest broadcasting increased cover crop biomass by 90%, to 1.29 Mg ha^{-1} for RYE and 0.87 Mg ha^{-1} for MIX1 in soybean–corn, and to 0.56 Mg ha^{-1} and 0.39 Mg ha^{-1} in corn–corn, respectively. At the drier site, post-harvest drilling increased biomass of RYE and MIX1 by 95% to 0.80 Mg ha^{-1} in soybean–corn. Biomass N uptake was highest in pre-harvest RYE and MIX1 at two sites in soybean–corn (35 kg ha^{-1}). RYE and sometimes mixes reduced soil N, but effects on P, K, and soil organic C were inconsistent. In soybean–corn, corn yields decreased by 4% after RYE, and in corn–corn, by 4% after pre-harvest cover crops. Site-specific selection of cover crops and planting practices can increase their performance while minimizing impacts on corn.

Abbreviations: CON, control without cover crops; GDD, growing degree days; LEGU, legume cover crop blend consisting of hairy vetch and winter pea; MIX1, cover crop mix consisting of cereal rye, hairy vetch, winter pea, and radish; MIX2, cover crop mix consisting of cereal rye, hairy vetch, winter pea, radish, oat, collard, clover; RYE, cereal rye cover crop.

1 | INTRODUCTION

Cover crops are an important strategy to alleviate several environmental concerns in annual corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] cropping systems. Studies at the farm-scale and watershed-scale have shown cover crops can improve soil health indicators, such as aggregate stability, active C, respiration, and soil organic matter (Krupek et al., 2022; Wood & Bowman, 2021) and reduce soil nitrate leaching (Christopher et al., 2021; Hively et al., 2020). They may also improve agronomic production by suppressing weeds (Singh et al., 2020) and supplying nutrients to subsequent crops (Adeux et al., 2021). Cover crops are increasingly used in the midwestern United States. They are typically planted after the harvest of corn or soybean and terminated the following spring before planting the next crop. Different species are grown for different purposes: Winter cereals such as cereal rye (*Secale cereale* L.) are adapted to cold temperatures and can take up large amounts of N stemming from soil mineralization at a time of non-existent crop N demand (Martinez-Feria et al., 2018). Brassicas are less tolerant of cold temperatures but can produce more biomass in the fall than winter cereals (Rosa et al., 2021). Both can suppress weeds during different times of the growing season. Legumes can improve yields and reduce fertilizer needs by supplying biologically fixed N to corn (Adeux et al., 2021; Perrone et al., 2020). Cover crop species are often combined in mixes to increase diversity and environmental benefits, although they are not always more productive than single plantings (Florence & McGuire, 2020).

In Nebraska alone, cover crop land area more than doubled between 2012 and 2017; however, cover crops still are only used on about 3.4% of cropland (USDA-NASS, 2019). Farmers in this region have identified several challenges to their adoption, with the main one being the establishment of the cover crop before winter (Oliveira et al., 2019). Soybean and corn harvest often coincides with the onset of hard freezes, limiting the growing season available for a cover crop planted after harvest and resulting in low biomass production. Several factors determine cover crop biomass production, most importantly attaining enough growing degree days (GDD). Earlier planting, for example by broadcast interseeding cover crops into maturing corn and soybean stands in late summer, increases access to GDD and precipitation and can result in greater productivity than post-harvest drill planting (Koehler-Cole, Elmore, et al., 2020). On the other hand, broadcasting often lowers seed germination which reduces stand counts and productivity (Haramoto, 2019). In contrast to seeds deposited in the soil, seeds on the soil surface cannot access soil moisture for germination, thus rely on timely and sufficient precipitation to meet their moisture requirements (Koehler-Cole, Elmore et al., 2020; Wilson et al., 2013). Compared to drill-planting after harvest, broadcast interseeding using an airplane or high-clearance equipment is faster (St Aime et al., 2022; Wilson et al., 2019) and less expensive (Plastina et al., 2021). Planting costs can vary greatly depending on location, cover crop species, seeding rate, and other factors.

Core Ideas

- Pre-harvest broadcast cover crops had greatest productivity in sites with wetter fall weather.
- Cereal rye was the most productive cover crop, followed by mixes.
- Cereal rye and sometimes mixes lowered soil N.
- Cover crop effects on soil P, soil K, and soil C were small.
- Cover crops reduced corn yields by 4% or less.

Cover crop biomass production may also be influenced by the preceding crop (Koehler-Cole & Elmore, 2020). In the western Corn Belt, no-till management of soils is prevalent and cover crops are directly planted into corn or soybean stubble remaining after harvest. Corn fields have greater amounts of residue than soybean fields, especially where corn is grown continuously. Remaining crop residue may block sunlight, reduce soil evaporation, and decrease soil temperatures (Shen et al., 2018). These differences can impact the establishment, growth, and productivity of cover crops, but have not received much attention in research. Regional differences in climate and soils also influence cover crop performance and inform management decisions at the local level.

A cover crop's ability to achieve desired functions can be indicated by several parameters. Biomass N of cereal and brassica cover crops can estimate their ability to reduce soil nitrate loss. In legumes, biomass N is associated with their potential to provide biologically fixed N to a subsequent crop. Carbon sequestration and changes in soil organic C may be dependent on biomass C content of a cover crop. Biomass C/N ratio affects residue decomposition rate and the return of nutrients to the soil. Lower C/N ratios decompose faster while higher C/N ratio biomass decomposes slower and may immobilize N (Sievers & Cook, 2018). All plants have low C/N ratios during early growth stages, however during later vegetative and reproductive development, cereals have greater C/N ratios than legumes. Cereals thus may retain N, whereas legumes may be an N source to the following crop (Lacey et al., 2020; Sievers & Cook, 2018). While these cover crop parameters are correlated to biomass production (Hively et al., 2020, Sing et al., 2020), it is not clear whether they also may interact with cover crop planting practice or the cropping system.

Cover crops have the potential to improve soil health, but their effects on corn yields can be variable and may depend on cover crop species and the region where they are grown, among other factors. In a review of 65 studies, cereal cover crops had neutral effects and mix and legume cover crops positive effects on corn yields. Whether cover crops were broadcast interseeded before harvest or drill-planted after harvest had no effect (Marcillo & Miguez, 2017). Cover crops may improve corn yield stability due to increased soil water storage (Leuthold et al., 2021) or may reduce corn yields in drier areas of the western Corn Belt due to soil water depletion (Rosa et al., 2021).

The objectives of our study were to investigate the effects of different cover crops, established with two planting practices in different regions of Nebraska on (a) cover crop productivity (biomass, C and N uptake), (b) soil nutrient concentrations, and (c) corn productivity (biomass and yields). We hypothesized pre-harvest broadcast planting would increase cover crop productivity compared to post-harvest drill planting. We further hypothesized cereal rye would be most productive, mixes intermediate and legumes least productive. We expected soil nutrient concentrations would decrease under pre-harvest broadcast planting and under cereal rye. Lastly, we predicted that cover crops would not influence corn productivity.

2 | MATERIALS AND METHODS

The experiments were located at three University of Nebraska-Lincoln research farms: (a) South-Central Agricultural Laboratory near Clay Center (40˚34′ N, 98˚08′ W; 552 m asl; transition between subhumid and semi-arid, USDA hardiness zone 5b; 689 mm annual precipitation), (b) Haskell Agricultural Laboratory near Concord (42˚22′ N, 96˚57′ W; 438 m asl; subhumid, zone 5a; 755 mm annual precipitation); and (c) Eastern Nebraska Research and Extension Center near Mead (41˚09′ N, 96˚24′ W; 347 m asl; subhumid; zone 5b; 768 mm annual precipitation). Clay Center fields had predominantly Hastings silt loam (fine, montmorillonitic, mesic Udic Argiustoll). Concord soil was Baltic silty clay (fine, montmorillonitic, mesic Cumulic Haplaquoll). Mead soil was Sharpsburg silty clay loam (fine, montmorillonitic, mesic Typic Argiudoll). The Clay Center site was irrigated June–August. The Concord and Mead sites were rainfed. Previous studies contain detailed information on soil physical properties (Ruis et al., 2020) and irrigation management (Barker et al., 2018) for these trials.

2.1 | Experimental and treatment design

At each site, experiments were implemented in two adjacent fields. One field was cropped to corn in 2014, soybean in 2015, corn in 2016, soybean in 2017, and corn in 2018; we will denote this cropping sequence as soybean–corn. The other field was cropped to continuous corn since 2014, and termed corn–corn cropping sequence. A third field was in a soybean–corn–soybean–corn sequence during the same time, but results are reported separately (Koehler-Cole, Elmore, et al., 2020). In each cropping sequence, the experimental design was randomized complete blocks with either three (Mead) or four replications. Treatments were applied to plots measuring 6 by 9 m at Clay Center, 6 by 12 m at Concord, and 4.5 by 9 m at Mead. The treatments were cover crop and cover crop planting practice, arranged as factorials. There were five cover crop treatments (Table 1): (a) Pure planted ‘Elbon’ cereal rye (RYE); (b) a mix of cereal rye, ‘Nitro’ forage radish (*Raphanus sativus* L.), hairy vetch [*Vicia villosa* Roth, variety not stated (VNS)] and ‘Whistler’ winter pea (*Pisum sativum* L.) (MIX1); (c) a mix of cereal rye, ‘Cosaque’ black oat (*Avena strigosa* Schreb.), ‘Impact’ forage collard (*Brassica oleracea* L.), radish, hairy vetch, winter pea, and either balansa clover (*Trifolium michelianum* Savi., VNS) or red clover (*Trifolium pratense* L., VNS) (MIX2); (d) a legume mix of hairy vetch and winter pea (LEGU), and (e) a no-cover crop control (CON). Legumes were inoculated with species-specific *Rhizobium* in powder form just prior to planting. Seeding rates for the cover crops were adjusted for seed purity and germination (Table 1). Planting practices were pre-harvest broadcast interseeding in corn and soybean stands in September, and post-harvest drill seeding after corn and soybean harvest in October–November (Table 2). These are the two most common planting practices to establish cover crops in Nebraska (Oliveira et al., 2019).

2.2 | Plot management

All experimental plots were in no-till management. We pre-harvest broadcast planted cover crops by hand at Clay Center and Mead, and with a one-row cone seeder at Concord, when corn had reached R5.5 stage (Abendroth et al., 2011) and soybean was at R6 or R7 (Pedersen, 2014) (Table 2). Pre-harvest broadcasting is comparable to broadcast interseeding with high-clearance equipment or an airplane. Following corn and soybean harvest, post-harvest drill treatments were planted with a 3P606 No-Till Great Plains drill (Great Plains Inc.) at a depth of 2.5 cm in 0.18-m rows (Table 2). This was a compromise between the recommended deeper seeding rates of cereal, oat, and legumes, and the shallower seeding rates of brassicas and clover.

Herbicide, fertilizer, and irrigation application were the same for cover crop and no-cover crop (CON) treatments, within a site. In spring, cover crops were terminated with 0.26 kg a.i. ha^{-1} glyphosate [*N*-(phosphonomethyl)glycine]. Nitrogen fertilizer in the form of liquid urea ammonium nitrate (UAN) was applied pre-plant to corn in the spring at all sites (Table 2) with site-specific rates (Table 3). A starter

TABLE 1 Seeding rates (in seeds m^{-2}) for cover crops planted in corn–corn and soybean–corn cropping sequences at three sites in Nebraska. Some species and seeding rates differed between years of the study. The total seeding rate per cover crop type is given in seeds m^{-2} and in kg ha^{-1}. Cover crops were cereal rye (RYE), a blend of hairy vetch + winter pea (LEGU), a mix of cereal rye + hairy vetch + winter pea + radish (MIX1), and a mix of cereal rye + hairy vetch + winter pea + radish + collards + clover (MIX2)

	Seeding rate								
Cover crop	Cereal rye	Radish	Hairy vetch	Winter pea	Collards	Balansa clover	Black oat	Total	
	seeds m^{-2}								kg ha^{-1}
Years 1 and 2									
RYE	300							300	67
LEGU			30	24				54	39
MIX1	150	20	10	8				188	52
MIX2	100	15	8	6	100	150	70	449	57
Years 3 and 4									
RYE	300							300	67
LEGU			54	36				90	78
MIX1	150		20	16	150			336	69
MIX2	100		15	12	100	150	70	447	74

fertilizer of 20 kg N ha^{-1} was used at Clay Center. At Concord and Mead, fertilizer was also applied during the corn growing season (Tables 2 and 3).

Corn was no-till planted into the cover crop residue in 0.75 m rows in late April to mid-May (Tables 2 and 3). Weeds were controlled with glyphosate, bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) (tradename buctril) and glufosinate [(*RS*)−2-Amino-4(hydroxy(methyl)phosphonoyl)butanoic acid], depending on site (Table 3). Herbicides with longer residual effects were omitted to avoid injury to subsequently planted cover crops. Plots at Clay Center were irrigated with 3.4 cm of water per pass for a total of six to seven passes in July and August with an overhead linear irrigation system. In the fall, the same cover crop treatments were established again in the same plots.

2.3 | Measurements

Cover crop productivity was assessed by measuring cover crop biomass, biomass C uptake, and biomass N uptake. Biomass was sampled just before termination in the spring (Table 2). Two 0.3 × 1.5 m frames were laid perpendicular to the rows, the first frame from the center of the second interrow to the center of the fourth interrow, and the second frame from the center of the fourth interrow to the center of the sixth interrow. All cover crops within the frames were clipped at the soil surface, dried at 60˚C to constant weight, and weighed. Weeds were rarely present at the time of biomass sampling and were not clipped.

Biomass was analyzed for C and N concentrations by elemental combustion analysis except in the 1st year. For MIX1, MIX2, and LEGU treatments, all species were combined, ground using a Wiley mill, and analyzed on a LECO TruMac Nitrogen/Carbon Analyzer (LECO Corporation) at Ward Laboratories. Cover crop C and N uptake on a kg ha^{-1} basis were calculated by multiplying C and N concentrations in percent with the amount of biomass in kg ha^{-1}. The C/N ratio was obtained by dividing biomass C by biomass N.

Soil samples were collected each spring by taking four soil cores to a depth of 0.2 m in each plot. Samples were analyzed at Ward Laboratories on a Lachat Flow Injection Analyzer (Lachat Instruments) using calcium phosphate to determine concentrations of nitrate and the Mehlich III method for P. Potassium was extracted with ammonium acetate and analyzed with an Inductively Coupled Argon Plasma instrument. Soil organic C was measured using elemental combustion on a LECO TruMac Nitrogen/Carbon Analyzer.

Corn productivity was measured by sampling corn biomass (stover), C and N uptake, and corn grain yields. Corn biomass at physiological maturity was assessed by cutting six consecutive corn plants in a nonharvest row, removing the cob with grain from each plant, shredding the remaining plant which consisted of the stalk, leaves, tassel, and husk leaves, and drying the shredded material at 60˚C to constant weight. A subsample of the biomass was analyzed at Ward Laboratories for C and N concentrations using elemental combustion. Corn biomass was only collected in Years 3 and 4 at Clay Center and Concord. Further, only biomass of corn growing after RYE and CON was sampled, because we expected these treatments to show the largest differences, based on previous data (Bastidas, 2017). Corn grain was harvested in October or November (Table 1) with a small plot combine from the center two rows of each plot and yields were adjusted to 15.5% moisture.

TABLE 2 Corn, soybean, and cover crop management and sampling dates for all site years, 2014–2018, in Nebraska

Activity	Clay Center	Concord	Mead
2014–2015			
Pre-harvest broadcast into corn	18 Sept. 2014	18 Sept. 2014	Sept. 8, 2014
Pre-harvest broadcast into soybean	9 Sept.	10 Sept.	8 Sept.
Pre-harvest drill after soybean	21 Oct.	28 Oct.	23 Oct.
Post-harvest drill after corn	21 Oct.	28 Oct.	23 Oct.
Soil nitrate sampling	–	–	–
CC biomass sampling	15 Apr. 2015	13 Apr. 2015	15 Apr. 2015
CC termination	15 Apr.	17 Apr.	16 Apr.
Pre-plant fertilization	1 Apr.	22 Apr.	8 Apr.
Corn planting	1 May	27 Apr.	29 Apr.
In-season fertilization	–	27 June	–
In-season weed control	Late May	June	June
2015–2016			
Pre-harvest broadcast into corn	3 Sept. 2015	10 Sept. 2015	3 Sept. 2015
Pre-harvest broadcast into soybean	4 Sept.	10 Sept.	9 Sept.
Soybean harvest	7 Oct.	13 Oct.	9 Oct.
Post-harvest drill after soybean	12 Oct.	16 Oct.	14 Oct.
Corn harvest	27 Oct.	13 Oct.	26 Oct.
Post-harvest drill after corn	early Nov.	16 Oct.	early Nov.
Soil nitrate sampling	8 Apr. 2016	16 May 2016	1 Apr. 2016
CC biomass sampling	13 Apr.	22 Apr.	15 Apr.
CC termination	22 Apr.	23 Apr	15 Apr.
Pre-plant fertilization	26 Apr.	17 May	5 May
Corn planting	12 May	6 May	6 May
In-season fertilization	–	–	28 June
In-season weed control	Mid-June	15 June, 4 July	6 June, 16 June
2016–2017			
Pre-harvest broadcast into corn	30 Aug. 2016	8 Sept. 2016	8 Sept. 2016
Pre-harvest broadcast into soybean	1 Sept.	8 Sept.	6 Sept.
Soybean harvest	10 Oct.	14 Oct.	23 Oct.
Post-harvest drill after soybean	14 Oct.	2 Nov.	26 Oct.
Corn harvest	18 Oct.	1 Nov.	10 Nov.
Post-harvest drill after corn	21 Oct.	2 Nov.	11 Nov.
Soil nitrate sampling	10 Apr. 2017	17 Apr. 2017	3 Apr. 2017
CC biomass sampling	13 Apr.	20 Apr.	18 Apr.
CC termination	25 Apr.	9 May	25 Apr.
Pre-plant fertilization	early May	12 May	6 Apr.
Corn planting	8 May	15 May	12 May
In-season fertilization	–	15 June.	30 June
In-season weed control	18 May	6 June, 22 June	15 June
2017–2018			
Pre-harvest broadcast into corn	7 Sept. 2017	8 Sept. 2017	11 Sept. 2017
Pre-harvest broadcast into soybean	4 Sept.	8 Sept.	11 Sept.
Soybean harvest	Mid-Oct.	17 Oct.	8 Nov.
Post-harvest drill after soybean	Late Oct.	8 Nov.	22 Nov.
Corn harvest	Late Oct.	3 Nov.	10 Nov.

(Continues)

TABLE 2 (Continued)

Activity	Clay Center	Concord	Mead
Post-harvest drill after corn	Late Oct.	8 Nov.	22 Nov.
Soil nitrate sampling	23 Apr. 2018	30 Apr. 2018	20 Apr. 2018
CC biomass sampling	16 Apr.	27 Apr.	19 Apr.
CC termination	24 Apr.	16 May	1 May
Pre-plant fertilization	Late Apr.	8 May	25 Apr.
Corn planting	Early May	24 May	17 May
In-season fertilization	–	–	20 June
In-season weed control	Mid-June	17 July.	28 June
Corn harvest	Late Oct.	29 Oct.	19 Oct.

Monthly temperature and precipitation data were obtained from the High Plains Regional Climate Center from stations located at Harvard near Clay Center, Concord, and Mead, and were averaged over the 4 yr of this study, since weather data for each site-year has been reported (Koehler-Cole, Elmore, et al., 2020).

2.4 | Statistical analyses

We used SAS 9.4 (SAS Institute) with an ANOVA for each cropping sequence (soybean–corn and corn–corn) because cropping sequence was not a factor in the treatment design. Data were checked for normal distribution using the UNIVARIATE procedure and if data were found to be non-normal, the ddfm = kr option was used in the model statement in the GLIMMIX procedure. To evaluate whether the variances were homogenous, residual values were plotted against predicted values. If obvious patterns existed, the variances were presumed to be nonhomogenous. Where data were nonhomogenous, a random residual statement with a group option was added in GLIMMIX. For the final model, site, cover crop treatment, and planting practice were considered fixed effects. The interaction of block, site, and year was the random effect. The LSMEANS statement was used to obtain estimates of the significant effects at the $\alpha = .05$ level. Within a site, significant effects of planting practice, cover crop treatment or their interaction were compared with the slicediff option.

3 | RESULTS AND DISCUSSION

3.1 | Weather

Weather varied greatly between years and is reported in detail in Koehler-Cole, Elmore, et al. (2020). The mean annual temperature and precipitation from 2015 to 2018 at Clay Center (south-central Nebraska) was 10.8˚C and 741 mm, at Concord (northeastern Nebraska) it was 9.2˚C and 750 mm, and at Mead (eastern Nebraska) it was 10.8˚C and 791 mm, respectively. During these years, the average monthly temperature at the eastern sites was at least 1˚C greater than the 30-yr normal for each month that cover crops were in the field (September–April), except for February and April which were similar to the 30-yr normal. At Clay Center, the average monthly temperatures for September, October, and January were at least 1˚C higher. At all sites, March was the month with the greatest deviation from the 30-yr normal and was about 2˚C warmer. However, mean precipitation during the cover crop growing period at Concord was 30 mm and at Clay Center 85 mm lower than the 30-yr normal.

3.2 | Cover crop productivity

In both cropping sequences, the site × cover crop treatment × planting practice interaction influenced cover crop productivity (Table 4). Thus, we will discuss the interaction of cover crop treatment and planting practice by site. In the soybean–corn sequence, biomass production increased in the order of LEGU < mixes < RYE with a maximum of 1.43 Mg ha^{-1} for pre-harvest broadcast RYE at Mead (Figure 1). At Clay Center, post-harvest drilling increased biomass of RYE and MIX1 by 74% compared to pre-harvest broadcast planting. Within each planting practice, RYE and the mixes had similar biomass. At Concord, pre-harvest broadcasting compared to post-harvest drilling increased biomass by 150% in RYE, MIX1, and MIX2, to an average of 0.82 Mg ha^{-1}. At Mead, the site with the greatest cover crop productivity, pre-harvest broadcasting increased RYE and MIX1 biomass by 272% to 1.26 Mg ha^{-1}. Within a planting practice, RYE and the mixes had similar biomass, however, at each site, the least productive RYE treatment still had similar biomass to the most productive non-RYE treatment. Legume biomass at all sites was <0.1 Mg ha^{-1} and not influenced by planting practice.

In the corn–corn sequence, cover crops had considerably lower amounts of biomass than in the soybean–corn sequence, 0.26 Mg ha^{-1} averaged across all treatments

TABLE 3 Fertilizer, corn cultivars, relative maturity (RM) and population, and herbicide inputs for each site year in Nebraska

Inputs	Mead	Concord	Clay Center
2014–2015			
Fertilizer (N in kg ha^{-1})			
Pre-plant soybean–corn	115	125	220
Pre-plant corn–corn	170	170	220
At plant (starter)	None	None	20
In-season soybean–corn	None	105	None
In-season corn–corn	None	160	None
Corn			
Cultivar, RM	Dekalb 61-88RIB, 111 RM	LG 5524VT3PRIB, 105 RM	Channel DKC 60-67RIB, 110 RM
Population, seeds ha^{-1}	65,000	60,900	85,000
Herbicides, a.i. in kg ha^{-1}			
Pre-plant[a]	Glyphosate, 1.78	Glyphosate, 1.30	Glyphosate, 1.78
In-season [b]	Glyphosate, 2.13	Glyphosate, 1.42	Glyphosate, 1.78
2015–2016			
Fertilizer (N in kg ha^{-1})			
Pre-plant soybean–corn	125	125	180
Pre-plant corn–corn	180	170	220
At plant (starter)	None	None[c]	20
In-season soybean–corn	85	na[d]	None
In-season corn–corn	85	na	None
Corn			
Cultivar	Dekalb 61-88RIB, 111 RM	LG 5524VT3PRIB, 105 RM	Channel 207-27STXR1B, 107 RM
Population, seeds ha^{-1}	65,000	60,900	85,400
Herbicides, a.i. in kg ha^{-1}			
Pre-plant	Glyphosate, 1.78	Glyphosate, 1.78	Glyphosate, 1.78
In-season	Bromoxynil0.28; glyphosate 2.49	Glufosinate, 0.45	Bromoxynil 0.28; glyphosate 1.78
2016–2017			
Fertilizer (N in kg ha^{-1})			
Pre-plant soybean–corn	120	110	180
Pre-plant corn–corn	170	110	220
At plant (starter)	None	None	20
In-season soybean–corn	85	na	None
In-season corn–corn	85	na	None
Corn			
Cultivar	Pioneer 1197AM, 111 RM	TitanPro 82 × 06, 106 RM	Channel, 209-53STXRIB, 109 RM
Population, seeds ha^{-1}	65,000	61800	84,000
Herbicides, a.i. in kg ha^{-1}			
Pre-plant	Glyphosate, 1.78	Glyphosate, 1.29	Glyphosate, 2.13
In-season	Glufosinate, 0.60	Glufosinate, 0.45	Bromoxynil 0.28; glyphosate 1.78
2017–2018			
Fertilizer (N in kg ha^{-1})			
Pre-plant soybean–corn	140	110	180
Pre-plant corn–corn	192	110	220
At plant (starter)	None	None	20

(Continues)

TABLE 3 (Continued)

Inputs	Mead	Concord	Clay Center
In-season soybean–corn	62	110	None
In-season corn–corn		110	None
Corn			
Cultivar	Pioneer 1197AM, 111 RM	Channel 203-01VT2PRIB, 103 RM	Channel 209-53STXRIB, 109 RM
Population, seeds ha^{-1}	65,000	61800	84,000
Herbicides, a.i. in kg ha^{-1}			
Pre-plant	Glyphosate, 1.78; 2,4-D 0.26	Glyphosate, 1.07	Glyphosate, 2.13
In-season	Glufosinate, 0.41	Glyphosate, 1.42	Bromoxynil 0.28; glyphosate 1.78

[a]Pre-plant is the herbicide applied for cover crop termination, active ingredient amount in kg ha^{-1}.
[b]Total amount applied if there were several applications.
[c]None, input not applied.
[d]na, information on input not available.

TABLE 4 Source of variation, degrees of freedom (df) and *P* values for over crop biomass and biomass parameters C uptake, N uptake, and C/N ratio in the soybean–corn and corn–corn sequence

Sources of variation	df	Soybean–corn				Corn–corn			
		Biomass	C uptake	N uptake	C/N	Biomass	C uptake	N uptake	C/N
Site (S)	2	.126	.118	.034	.111	.055	.106	.031	.520
Cover crop (C)	3	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
S × C	6	.479	.244	.110	.830	.269	.225	.117	.949
Planting practice (P)	1	<.001	.037	.122	.084	<.001	<.001	<.001	<.001
S × P	2	<.001	<.001	<.001	.015	<.001	<.001	<.001	.244
C × P	3	.016	.210	.365	.295	<.001	<.001	.001	.922
S × C × P	6	<.001	.001	.011	.142	<.001	.097	.034	.472

Note: Biomass data is from all 4 yr, but C uptake, N uptake, and C/N are from 3 yr.

(Figure 1; Table 4). At Concord and Mead, pre-harvest planting increased biomass of RYE and mixes compared to post-harvest planting by about 140% at Concord and 240% at Mead. When pre-harvest planted, RYE was more productive than the mixes, by about 84% at Concord and 230% at Mead, but in the post-harvest plantings, RYE and mixes had similar biomass. However, even the pre-harvest RYE produced only modest amounts of biomass, 0.82 Mg ha^{-1} at Concord and 1.02 Mg ha^{-1} at Mead. At Clay Center, planting practice did not influence biomass of any cover crop treatment, which was 0.22 Mg ha^{-1} for RYE and mixes. Here and at the other sites, LEGU biomass was insignificant and did not respond to planting practice.

In both cropping sequences, pre-harvest broadcast interseeding resulted in more biomass than post-harvest drill planting at Mead and Concord, but not at Clay Center. Broadcast seeds have reduced access to soil moisture due to their lack of seed-soil contact. They require timely rainfall after planting, ideally within 7 d (Wilson et al., 2013) and an optimum amount of 28 mm (Koehler-Cole, Elmore, et al., 2020). Where these rainfall requirements are not met, such as in Clay Center which has drier falls than Concord and Mead, post-harvest drill planting results in more productive cover crops. Similar findings were reported in a study that investigated cover crop planting practices in the corn–soybean cropping sequence (Koehler-Cole, Elmore, et al., 2020) and outside the Corn Belt in Kentucky (Haramoto, 2019). In a study in Maryland (Moore & Mirsky, 2020) post-harvest drill planting resulted in more cover crop biomass than broadcast interseeding in dry years. Conclusions were limited, because these studies had only one site and 2 (Haramoto, 2019) or 3 (Moore & Mirsky, 2020) yr. Furthermore, in the Kentucky study, cover crops were established on the same day, whereas in our study and the study from Maryland, the pre-harvest broadcast interseeding was done 6–8 wk before the post-harvest drill planting, increasing GDD and precipitation available to cover crop seedlings. In fact, every additional day of cover crop growth before 31 October can result in 0.062 Mg ha^{-1} more biomass per day in the western Corn Belt (Chatterjee et al., 2020).

Our most productive cover crop was RYE, in line with other studies in the Corn Belt (Appelgate et al., 2017; Cornelius & Bradley, 2017). Moderate productivity of post-harvest drill planted RYE in soybean–corn sequences are common in this

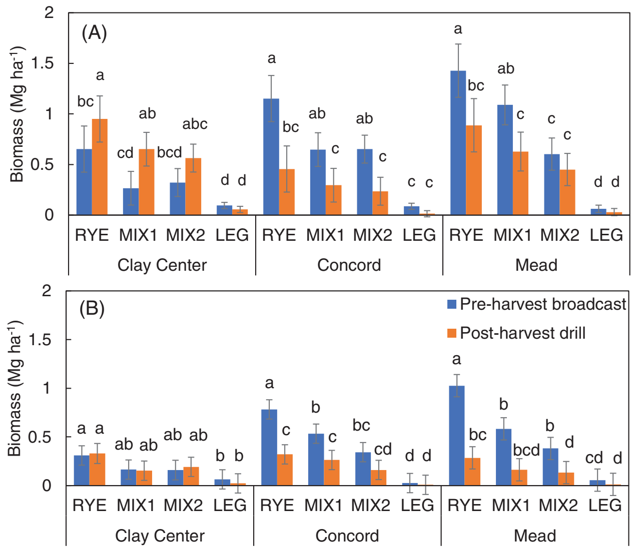

FIGURE 1 Cover crop biomass in the (A) soybean–corn and (B) corn–corn sequence at each site in Nebraska. Cover crops were cereal rye (RYE), hairy vetch + winter pea (LEGU), cereal rye + hairy vetch + winter pea + radish (MIX1), and cereal rye + hairy vetch + winter pea + radish + collards + clover (MIX2), planted either by pre-harvest broadcasting (blue bars) and or post-harvest drilling (red bars). Standard errors are indicated by lines above the bars. Within each site, bars with the same letter are not significantly different from each other at α = .05

region, with 0.76 Mg ha^{-1} (Appelgate et al., 2017), 1.28 Mg ha^{-1} (Pantoja et al., 2016), and 1.09 Mg ha^{-1} (Ruis et al., 2017). Studies with pre-harvest broadcasting report somewhat higher RYE biomass, 1.47 Mg ha^{-1} (Blanco et al., 2017) and 2.32 in Mg ha^{-1} (Koehler-Cole & Elmore, 2020). For high biomass production, for example to reach the 1 Mg ha^{-1} threshold for soil nitrate reduction (Hively et al., 2009), RYE is preferable over mixes, and should be established using pre-harvest broadcast seeding in cooler, wetter sites, and post-harvest drill planting in warmer, drier sites of the western Corn Belt.

The LEGU treatment which consisted of hairy vetch and winter pea had insignificant biomass production, likely due to their greater basal temperature and GDD requirement. Legumes often did not emerge in the post-harvest drill planting because it was too cold. In recent studies in Nebraska pre-harvest broadcast hairy vetch produced 0.36–0.54 when terminated by early May in eastern sites (Koehler-Cole & Elmore, 2020) and 0.81 Mg ha^{-1} when drill-planted by September and terminated in May in drier, western sites (Rosa et al., 2021). Winter pea is less cold hardy than hairy vetch (Vann et al., 2021) but cultivars suitable to Nebraska produced 0.7 Mg ha^{-1} biomass in dryland and 2.74 Mg ha^{-1} in irrigated conditions by mid-June (Homer et al., 2019). Legumes may become more attractive cover crops due to the current high fertilizer prices, but to achieve greater biomass and N_2 fixation, growers need to improve legume management. This includes selecting high-performing, locally adapted cultivars, appropriate inoculation, planting earlier and terminating later to increase access to GDD and soil moisture, or considering irrigation where possible.

In most sites, MIX1 and MIX2 had similar productivity but only reached 1 Mg ha^{-1} at Mead, in the pre-harvest planting. Although cereal rye did not make up most of the seeds in the mixes (Table 1) it produced most of the biomass in the spring. Brassicas winterkilled and legumes had very little growth, as discussed above. Mixes increase agroecosystem diversity and may provide more ecosystem services than monoculture cover crops, but only if GDD and precipitation requirements of all species in the mix are met.

Crop sequence likely played a role in cover crop productivity, although it was not a factor in the statistical analysis. Low productivity in continuous corn could be due to high corn residue which may affect seed-soil contact, cover crop emergence, and growth in several ways. In studies comparing soil temperature under corn and soybean residues, soil temperature at 0.1-m depth was up to 1.9˚C lower under corn residue than under soybean residue following planting (Shen et al., 2018). Residue also alters the ratio of red/far-red light which inhibits germination of seeds and acts as a physical barrier to seedling growth (Teasdale & Mohler, 1993). In addition, continuous corn systems may have lower soil residual N which could impair cover crop growth. Evidence that cover crops established in soybean are up to 50% more productive than in the corn phase has been documented (Koehler-Cole & Elmore, 2020), but the experimental design in that study did not allow for statistical comparisons of the cropping sequence. More systematic research that includes cropping sequence as an independent variable would allow us to make specific recommendations for cover crops established in corn–soybean, soybean–corn, and corn–corn sequences.

3.3 | Cover crop C and N uptake

Cover crop C content closely mirrored biomass production in both cropping sequences (Figure 2), with the highest C in RYE and MIX1, and lowest in MIX2 and LEGU in both cropping sequences. It peaked in the soybean–corn sequence in pre-harvest broadcast RYE and MIX1 at Mead with 0.56 Mg ha^{-1}. At the eastern sites, pre-harvest planting increased C in RYE and MIX1 but at Clay Center, post-harvest drilled RYE and MIX1 contained more C. At all sites, C content of MIX2 and LEGU did not differ between planting practice and was <0.2 Mg ha^{-1}. In the corn–corn sequence, RYE and MIX1 had 0.19 Mg C ha^{-1}, MIX2 0.05 Mg C ha^{-1}, and LEGU 0.02 Mg C ha^{-1}. Pre-harvest broadcast planting had greater C content at Concord and Mead, 0.16 Mg ha^{-1} and at 0.30 Mg ha^{-1}, but at Clay Center, both plantings had the same C content,

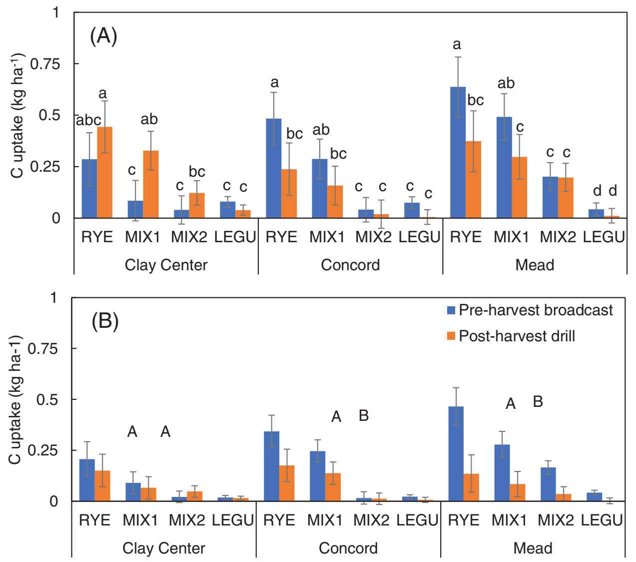

FIGURE 2 Cover crop C uptake in the (A) soybean–corn and (B) corn–corn sequence at each site in Nebraska. Cover crops were cereal rye (RYE), hairy vetch + winter pea (LEGU), cereal rye + hairy vetch + winter pea + radish (MIX1), and cereal rye + hairy vetch + winter pea + radish + collards + clover (MIX2), planted either by pre-harvest broadcasting (blue bars) and or post-harvest drilling (red bars). Standard errors are indicated by lines above the bars. Within each site, bars with the same letter are not significantly different from each other at α = .05. Upper-case letters denote significant differences in planting practice within a site

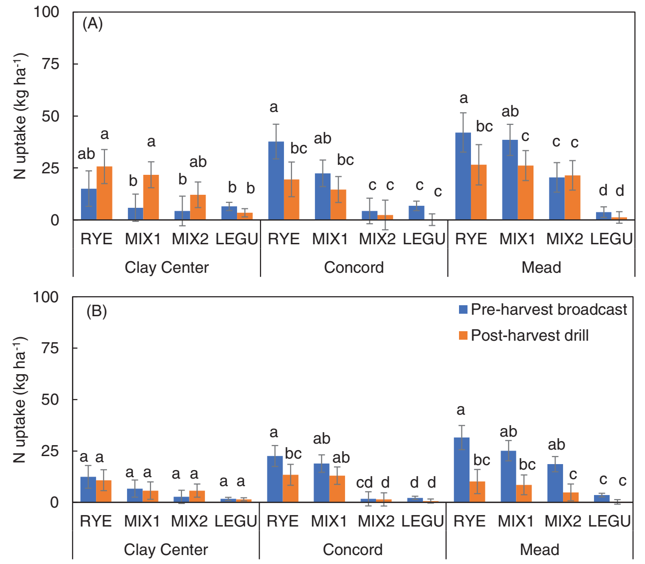

FIGURE 3 Cover crop N uptake in the (A) soybean–corn and (B) corn–corn sequence at each site in Nebraska. Cover crops were cereal rye (RYE), hairy vetch + winter pea (LEGU), cereal rye + hairy vetch + winter pea + radish (MIX1), and cereal rye + hairy vetch + winter pea + radish + collards + clover (MIX2), planted either by pre-harvest broadcasting (blue bars) and or post-harvest drilling (red bars). Standard errors are indicated by lines above the bars. Within each site, bars with the same letter are not significantly different from each other at α = .05

0.08 Mg ha^{-1}. Cover crop C may be an indicator for a cover crop's potential to sequester C from the atmosphere and is correlated with biomass production (Sunoj et al., 2021). Thus, the treatments with the greatest biomass also had the greatest C content and may have potential to increase soil organic C.

Nitrogen uptake in both cropping sequences, was in the order of RYE = MIX1 > MIX2 > LEGU. In soybean–corn, Clay Center had lower N uptake than the other sites, with an average of 20 kg ha^{-1} in the post-harvest plantings of RYE and mixes. At Concord and Mead, pre-harvest broadcast planting increased N uptake in RYE and MIX1 to an average of 30 kg ha^{-1} at Concord and 40 kg ha^{-1} at Mead. The lowest N uptake was in LEGU, averaging 4 kg ha^{-1} across sites and plantings (Figure 3). In the corn–corn sequence at Concord, pre-harvest planting increased RYE N uptake to 23 kg ha^{-1}, whereas N uptake for MIX1 was similar in both planting practices and was 16 kg ha^{-1}. At Mead, pre-harvest broadcasting RYE and the mixes had the greatest N uptake at 25 kg ha^{-1}, but the post-harvest plantings had only 8 kg ha^{-1}. At Clay Center, planting practice or cover crop treatment had no effect on N uptake, which was 6 kg ha^{-1}. At all sites, LEGU produced insignificant amounts of N, on average 2 kg ha^{-1} (Figure 3).

The RYE and mixes had the highest biomass N uptake, reflecting the ability of cereal rye, both when planted alone and in combination with other species, to scavenge soil N. This makes cereal rye an excellent cover crop to mitigate soil nitrate loss from crop fields, like areas of Nebraska where groundwater nitrate concentrations exceed levels considered safe for human consumption (Nebraska Department of Environment & Energy, 2019). Site-specific management methods can maximize N uptake by ensuring high biomass production, for example pre-harvest planting in sites with wetter and post-harvest planting in sites with drier conditions during cover crop seeding and designing cover crop treatments dominated by cereal rye. Legumes can take up N from the soil and the atmosphere through biological N_2 fixation by symbiotic *Rhizobia* bacteria. In regions with similar climates, hairy vetch derived between 38 and 100% of its biomass N from biological fixation (Perrone et al., 2020). In our study, visual observations in the spring showed nodules in hairy vetch and winter pea roots, signaling biological N_2 fixation. However, due to their lack of biomass production, LEGU N content overall was very small and was unlikely to play a role either in soil N scavenging or as an N supplier for the subsequent corn crop. Cover crops in the soybean–corn sequence had on average 9 kg ha^{-1} more N uptake than those in the corn–corn sequence, likely due to differences in biomass production and residual soil N.

Cover crop C/N ratios responded to the main effect of cover crop and the site × planting practice interaction in the soybean–corn and to the main effects of cover crop and

TABLE 5 Cover crop C/N ratio in the soybean–corn and corn–corn sequence at all sites in Nebraska. Cover crops were cereal rye (RYE), hairy vetch + winter pea (LEGU), cereal rye + hairy vetch + winter pea + radish (MIX1), cereal rye + hairy vetch + winter pea + radish + collards + clover (MIX2) and a noncover crop control treatment (CON)

Variable	C/N ratio Soybean–corn	C/N ratio Corn–soybean
Site		
Clay Center	11	10
Concord	10	10
Mead	12	11
Cover crop		
LEGU	10b	10b
MIX2	9c	9c
MIX1	11ab	11ab
RYE	13a	13a
Planting practice		
Pre-harvest broadcast	11	11ab
Post-harvest drill	11	10b
Site × Planting practice		
Clay Center		
Pre-harvest broadcast	11a	11
Post-harvest drill	11a	10
Concord		
Pre-harvest broadcast	11a	10
Post-harvest drill	10a	10
Mead		
Pre-harvest broadcast	12a	11
Post-harvest drill	11b	10

Note: Cover crops were planted either as a pre-harvest broadcast planting and or post-harvest drill planting. In each column, means followed by the same letter are not significantly different at α = .05.

planting practice in the corn–corn sequence (Tables 4 and 5). However, differences between treatments were small. In both sequences, RYE had the highest C/N at 13:1 and MIX2 had the lowest C/N ratio at 9:1 (Table 5). In the soybean–corn sequence at Concord and Clay Center, planting practice did not influence C/N ratio but at Mead, the pre-harvest broadcast planting increased C/N ratio compared to the post-harvest drill planting from 11:1 to 13:1. In corn–corn, pre-harvest broadcast planting had a C/N ratio of 11:1 and post-harvest drill planting had a 10:1 C/N ratio (Table 5). Cover crop C/N ratio impacts the rate of decomposition after termination which together with the amount of biomass N uptake can predict cover crop effects on corn nutrition and corn yields. Contrary to our expectations, all cover crops had low C/N, most likely because they were terminated in early vegetative stages. In another study where cover crops had similar C/N ratios, most biomass N was released within 4 wk (Sievers & Cook, 2018) which corresponds to the time when corn has the greatest N demand. Cover crop C/N ratios can increase quickly due to their rapid growth in the spring. For example, when terminated just 2 wk later, RYE had a C/N ratio of 15:1 and MIX1 had a C/N ratio of 18:1 (Koehler-Cole, Elmore, et al., 2020). Decomposing residue with high C/N can immobilize N in the soil (Lacey et al., 2020; Sievers & Cook, 2018), increasing the risk for N deficiencies and yield lag in corn.

3.4 | Cover crop effects on soil nutrients

The cover crop treatment × site interaction was significant for N, P, and K in both cropping sequences and is shown along with the main effects (Table 6). Other interactions were seldom significant and where they occurred will be discussed in the text. In the soybean–corn sequence, soil N was greater at Clay Center than Concord and Mead. RYE and MIX1 reduced soil N concentrations compared to the control treatment (CON) which did not have a cover crop. The simple effects had an impact at Mead, where RYE reduced soil nitrate concentrations compared to CON and at Clay Center, where RYE and the mixes reduced soil nitrate compared to CON (Table 6), but soil N was not influenced by cover crops at Concord. The planting practice × site interaction was significant (P = .001) only at Clay Center where post-harvest drilled cover crops decreased soil nitrate by 2 mg kg^{-1} (data not shown). In the corn–corn sequence at Clay Center, RYE and to a lesser extent the mixes decreased soil N compared to the CON and LEGU treatments. At Mead, only RYE decreased soil N and at Concord, cover crops did not influence soil N. Post-harvest drill plantings had more soil N than the pre-harvest broadcast plantings. At Clay Center, post-harvest drilled RYE reduced soil N by about 5 mg kg^{-1} compared to post-harvest drilled CON. At Concord soil N was decreased by pre-harvest RYE and MIX2 compared to CON by about 3 mg kg^{-1} (data not shown).

We expected the treatments with the greatest biomass and N uptake, in particular RYE, to reduce soil N, but the cover crop effects were site specific. At Mead, where RYE had high biomass and N uptake (Figures 1 and 3), RYE reduced soil N in the soybean–corn, but not the corn–corn sequence. However, at Clay Center, the site with the lowest cover crop biomass production and N uptake, RYE reduced soil N in both cropping sequences. At Concord, where RYE took up more N than at Clay Center, there was no effect on soil nitrate. It is possible that cover crop effects were more apparent at Clay Center because its soil N concentrations were about twice as high as those of the other sites, making least-square mean differences more distinguishable. Mixes were less effective than RYE, and LEGU did not impact soil nitrate at any site, due to its lack of biomass production. The effect of

TABLE 6 Soil nutrient (N, P, K) content in mg kg^{-1} and organic carbon content in g kg^{-1} in the soybean–corn sequence and corn–corn sequence at all sites in Nebraska

Variable	Soybean–corn				Corn–corn			
	N	P	K	C	N	P	K	C
	mg kg^{-1}			g kg^{-1}	mg kg^{-1}			g kg^{-1}
Site								
Clay Center	10a	24b	385b	17c	9a	18b	319b	18b
Concord	5b	34a	282c	24a	5b	30a	282b	26a
Mead	5b	13c	428a	19b	4b	10b	382a	17c
P value	<.001	<.001	<.001	<.001	.002	.002	.002	<.001
Cover crop								
LEGU	7a	26a	367	20	7a	17b	314b	20b
MIX2	6b	26a	368	20	6bc	21a	323ab	21a
MIX1	6bc	21b	357	20	6b	21a	337a	21a
RYE	5c	21b	370	20	5c	17b	327ab	21ab
CON	7a	23ab	363	20	7ab	21a	332a	20b
P value	<.001	.003	.784	.435	<.001	.001	.033	.013
Planting practice								
Pre-harvest broadcast	7	24	368	20	5b	19	324	20
Post-harvest drill	6	23	362	20	7a	20	330	20
P value	.066	.510	.326	.541	<.001	.155	.209	.531
Site × Cover crop								
Clay Center								
LEGU	11a	22a	374a	16	11a	17a	302b	18
MIX2	9b	25a	371a	17	8bc	18a	302b	18
MIX1	9b	23a	384a	17	9b	19a	319ab	18
RYE	8b	23a	400a	17	7c	17a	321ab	19
CON	12a	26a	397a	17	11a	20a	334a	18
Concord								
LEGU	5a	40a	313a	24	6a	27b	261b	26
MIX2	5a	40a	302ab	24	5a	35a	300a	27
MIX1	5a	29b	260b	24	5a	35a	297a	26
RYE	4a	29b	263b	24	5a	23b	258b	26
CON	5a	31b	271b	24	6a	33a	297a	26
Mead								
LEGU	6a	16a	413a	18	5a	8a	380ab	17
MIX2	5a	12a	432a	19	4ab	11a	368b	18
MIX1	4ab	11a	427a	19	4ab	10a	394ab	18
RYE	3b	12a	446a	19	3b	9a	402a	18
CON	5a	12a	422a	19	4ab	9a	366b	17
P value	.003	.009	.011	.141	.022	.021	<.001	.315

Note: Cover crops were cereal rye (RYE), hairy vetch + winter pea (LEGU), cereal rye + hairy vetch + winter pea + radish (MIX1), cereal rye + hairy vetch + winter pea + radish + collards + clover (MIX2) and a noncover crop control treatment (CON). Cover crops were planted either as a pre-harvest broadcast planting and or post-harvest drill planting. In each column, means followed by the same letter are not significantly different at α = .05.

planting practice on soil N was less pronounced, although planting practice plays a large role in biomass production and N uptake. Depending on cropping system and site, selecting a planting practice that results in greater N uptake could be reflected in lower soil N. A study from Indiana with cereal rye and other winter cover crops documented that cover crop biomass at spring termination was negatively correlated with decreased soil nitrate (Christopher et al., 2021). Decreased soil N of similar or greater magnitude than in our experiments were reported from other studies in the Corn Belt with comparable cover crop productivity (Appelgate et al., 2017; Christopher et al., 2021). This supports the argument of using cover crops as a strategy to lower soil nitrate and reduce leaching potential. While we did not measure actual nitrate leaching in our study, crop modelling under different scenarios predicted that cereal rye cover crops planted at optimum establishment times on 100% of cropland could reduce soil nitrate leaching by 85% (Hively et al., 2020), whereas other cereals and/or late planting times were less successful in decreasing nitrate leaching losses. These scenarios underline the importance of best management practices in reaching cover crop goals.

Soil P concentrations were highest at Concord and lowest at Mead (Table 6). In the soybean–corn sequence at Concord, LEGU and MIX2 increased soil P concentrations by about 33% compared to CON, RYE, and MIX1, but cover crops did not have an effect at the other sites. In the corn–corn sequence, LEGU and RYE decreased soil P concentrations compared to CON. Due to much greater soil P concentrations at Concord than at Mead and Clay Center, the results at Concord are driving the differences in the analysis of variance. We did not test cover crop biomass for P uptake, but during vegetative growth stages 0.4–0.8% of plant biomass is P (Shaver, 2014), thus cover crop P uptake was likely low. The treatments at Concord had opposing effects, depending on the crop sequence. These effects may be related to soil P uptake by the preceding corn or soybean crop, differences in cover crop root systems and P acquisition strategies, and differences in their ability to associate with mycorrhizal fungi (Hallama et al., 2019; Wendling et al., 2016). Inconsistent effects of cover crops on soil P have been documented at the watershed level, where cover crops decreased soil P in one watershed, but slightly increased P depending on soil depth in the other watershed (Christopher et al., 2021). Cover crops may be a more reliable tool to reduce soil N losses than soil P losses but because soil P concentrations following cover crops are rarely reported in studies, few inferences of cover crop treatments or planting practices on soil P can be made. Considering the role soil P plays in crop nutrition and as a contaminant in water bodies, cover crop studies should investigate soil P.

Soil K concentrations were highest at Mead. In the soybean–corn sequence, cover crop treatment only had an effect at Concord, where the LEGU treatment increased soil K concentrations compared to CON, RYE, and MIX1 (Table 6). In the corn–corn sequence at Mead, RYE increased soil K compared to CON and MIX2. At Concord, RYE and LEGU decreased soil K compared to CON and both mixes, whereas at Clay Center, LEGU and MIX2 reduced soil K compared to CON. Crop K uptake, although not measured in this experiment, is between 3.5 and 5% of biomass (Shaver, 2014). While others have found correlations between cover crop biomass and soil K (Wendling et al., 2016), there appears to be no association between those variables in our study. A long-term study with cover crops in Nebraska also found few differences in soil K due to cover crops, although there was some evidence that cover crops may maintain soil K concentrations deeper in the soil profile over time (Sharma et al., 2018). It should be noted that P and K changes due to cover crops in our study had lower magnitudes than N and may only have become evident because we grew cover crops continuously for 4 yr without adding P and K as fertilizers.

Soil organic C concentrations were greatest at Concord. In the soybean–corn sequence, cover crop treatment, planting practice and their interactions did not change soil organic C concentrations (Table 6). In the corn–corn sequence, MIX1 and MIX2 increased soil C by about 3% compared to CON. This effect is unexpected because mixes in this sequence had low C biomass content, only 0.05 Mg ha^{-1} for MIX2 and 0.15 Mg ha^{-1} for MIX1 (Figure 2). A trial that measured soil physical properties in these plots in the last year of the study (2018) found no changes in soil organic C but a 31% increase in particulate organic matter in the corn–corn sequence at Concord in pre-harvest broadcast cover crops (Ruis et al., 2020). Cover crop mixes may be more beneficial in continuous corn systems, because their low C/N biomass provides a more accessible source of N for soil microbes than corn stover and could increase turnover of stover C into soil organic C. Small but significant increases in soil organic carbon after 2 to 5 yr of cover cropping were also documented in a large, farm-scale level study across the Midwest (Wood & Bowman, 2021). A recent on-farm study from Nebraska discovered long-term cover crop use had more impact on organic matter and C and N dynamics than other soil health practices, such as reducing tillage, integrating livestock, or rotating crops (Krupek et al., 2022).

3.5 | Corn productivity

Subsequent corn crop stover was not affected by site, cover crop, planting practice, or their interactions. Stover was 3.68 Mg ha^{-1} in continuous corn and 4.0 Mg ha^{-1} in corn grown in rotation with soybean (Table 7). This was low compared with findings from other studies in the Midwest (O'Brien & Hatfield, 2021), because at the time of stover sampling in mid-October (Table 2), corn was senescing and losing leaves and tassels. In addition, some disease and weed pressure may have impacted corn growth in these site-years. Thus, our measurements underestimate the actual amount of corn stover in the field. Corn biomass C content was the same for all factors, with 1.57 Mg C ha^{-1} in the corn–corn sequence and 1.71 Mg C ha^{-1} in the soybean–corn sequence (Table 7). Where corn was grown continuously, corn N uptake was greater after RYE than after CON at Concord (45 and 35 kg ha^{-1}, respec-

TABLE 7 Corn biomass (stover) and stover C and N uptake in the soybean–corn and corn–corn sequence at all sites in Nebraska

Variable	Corn–corn				Soybean–corn			
	Stover	C	N	C/N	Stover	C	N	C/N
	———Mg ha^{-1}———		kg ha^{-1}		———Mg ha^{-1}———		kg ha^{-1}	
Site (S)								
Clay Center	4.27	1.82	34	51a	4.13	1.76	35	51
Concord	3.08	1.31	40	33b	3.87	1.65	39	45
P value	.209	.206	.508	<.001	.805	.81	.661	.164
Cover crop (C)								
CON	3.59	1.53	34b	43	3.94	1.68	36	47
RYE	3.76	1.61	40a	41	4.06	1.73	38	48
P value	.232	.19	.012	.154	.453	.453	.460	.646
Planting time (P)								
Pre-harvest broadcast	3.68	1.57	37	43	4.03	1.72	37	47
Post-harvest drill	3.67	1.56	37	42	3.96	1.69	37	49
P value	.97	.952	.951	.532	.652	.651	.861	.256
S × C								
Clay Center								
CON	4.18	1.78	34b	50a	3.97	1.69	34	50
RYE	4.36	1.87	35b	52a	4.28	1.83	35	52
Concord								
CON	3.00	1.27	35b	36b	3.91	1.67	38	45
RYE	3.16	1.34	45a	31c	3.83	1.63	40	45
P value	.943	.802	.034	.004	.220	.195	.918	.782
S × P								
Clay Center								
Pre-harvest broadcast	4.32	1.85	35	51	4.25	1.80	38a	47b
Post-harvest drill	4.22	1.80	34	51	4.00	1.71	32a	54a
Concord								
Pre-harvest broadcast	3.03	1.28	40	34	3.82	1.64	37a	46ab
Post-harvest drill	3.13	1.33	41	33	3.92	1.67	42a	43b
P value	.497	.441	.547	.485	.276	.364	.022[a]	.013
C × P								
Control								
Pre-harvest broadcast	3.63	1.54	35	44	4.02	1.72	36	47
Post-harvest drill	3.55	1.51	34	43	3.86	1.65	36	48
Rye								
Pre-harvest broadcast	3.73	1.59	40	42	4.05	1.73	38	47
Post-harvest drill	3.79	1.62	40	41	4.07	1.74	38	50
P value	.623	.625	.854	.951	.552	.564	.985	.761

Note: Stover was only sampled at two sites and two cover crops. In each column, means followed by the same letter are not significantly different at α = .05.
[a]*F* test was significant, but none of the ls means differences were significant at.05.

tively), but not at Clay Center. Continuous corn C/N ratios at Concord were lower after RYE than after CON. In corn that was grown in rotation with soybean, few parameters were impacted, except for C/N, which was greatest in the post-harvest drill planting at Clay Center, due to low N uptake (Table 6). Greater corn N uptake following RYE than following CON may have come from N released from decomposing cover crop biomass (Figure 3) and could indicate improved nutrition of continuous corn. Greater stover N uptake also resulted in lower stover C/N ratios, potentially increasing the rate of corn stover decomposition.

Corn yields in soybean–corn were impacted by site and cover crop type (Table 8). Clay Center is irrigated and had the highest corn yields, 14.85 Mg ha^{-1}, followed by Mead with 12.27 Mg ha^{-1}, and Concord with 10.83 Mg ha^{-1}. The highest yields were after CON and mixes, whereas RYE reduced corn yields by about 4%. Yields of continuous corn were influenced by site and planting practice. They were highest at Clay Center with 13.42 Mg ha^{-1}, then Mead with 10.54 Mg ha^{-1}, and Concord with 7.00 Mg ha^{-1}. Pre-harvest planted cover crops reduced continuous corn yields by 0.41 Mg ha^{-1} or 4% compared to post-harvest planted cover crops (Table 7).

Contrary to our expectations, RYE led to a small, but significant yield reduction in rotated corn. This could have been caused by N immobilization due to its high N uptake and slow release (Nevins et al., 2020). In our study, RYE took up 28 kg N ha^{-1} but MIX1 had similar N uptake (Figure 3) and did not cause corn yield reductions. MIX1 had a somewhat lower C/N ratio (Table 5) and may have released N from its biomass sooner than RYE following termination. Adjusting N fertilization to include a starter fertilizer or split N applications may overcome N immobilization issues.

In corn–corn, despite some evidence of improved corn nutrition following cover crops, yields were reduced by pre-harvest broadcast planted cover crops. Cover crop productivity was low in this sequence but cover crops may have been hosts for pathogens such as *Pythium* and *Fusarium* spp. (Acharya et al., 2017). Disease occurrence may be mitigated by placing corn rows at greater distance from cover crop residue (Kurtz et al., 2021) and delaying corn planting by 10–14 d after cover crop termination (Acharya et al., 2017). Allelopathic chemicals secreted by cover crops have stunted corn seedling growth in laboratory experiments, but allelopathic reactions are likely transient and have rarely been confirmed in the field (Koehler-Cole, Everhart, et al., 2020). Cover crop water use can have negative effects on subsequent crops (Rosa et al., 2021), but soil water measurements during the first 3 yr of this study revealed no deficits due to cover crops (Barker et al., 2018).

Corn yield lag of similar magnitude was reported in Iowa where corn followed cereal rye (Pantoja et al., 2015) and in Illinois where corn followed nonlegume cover crops (Qin et al., 2021). However, a review of cover crop studies across the United States and Canada found positive corn yield responses to cover crop mixes and neutral responses to grass cover crops (Marcillo & Miguez, 2017). Selecting a cover crop mix over RYE may avoid corn yield lag while still achieving several other functions such as reducing soil N and improving soil organic C.

TABLE 8 Corn grain yields (adjusted to 15.5% moisture) in the soybean–corn and corn–corn sequence, at all sites in Nebraska

Variable	Corn grain yield	
	Corn–corn	Soybean–corn
	Mg ha^{-1}	
Site (S)		
Clay Center	13.42a	14.85a
Concord	7.00c	10.83c
Mead	10.54b	12.27b
P value	<.001	<.001
Cover crop (C)		
LEGU	10.34	12.61ab
MIX2	10.34	12.73a
MIX1	10.37	12.83a
RYE	10.05	12.28b
CON	10.49	12.83a
P value	.233	.036
Planting practice (P)		
Pre-harvest broadcast	10.11b	12.56
Post-harvest drill	10.52a	12.75
P value	.001	.137
S × C		
Clay Center		
LEGU	13.03	14.51
MIX2	13.67	14.83
MIX1	13.63	15.34
RYE	13.29	14.47
CON	13.46	15.11
Concord		
LEGU	7.00	11.10
MIX2	7.09	10.99
MIX1	7.11	10.68
RYE	6.54	10.64
CON	7.25	10.76
Mead		
LEGU	11.00	12.22
MIX2	10.25	12.36
MIX1	10.37	12.46
RYE	10.32	11.74
CON	10.77	12.60
P value	.1731	.2705
S × C, *P* value	.1272	.1671
S × C, *P* value	.1699	.8637
S × C × P, *P* value	.6927	.4947

Note: Cover crops were cereal rye (RYE), hairy vetch + winter pea (LEGU), cereal rye + hairy vetch + winter pea + radish (MIX1), cereal rye + hairy vetch + winter pea + radish + collards + clover (MIX2) and a noncover crop control treatment (CON). Cover crops were planted either as a pre-harvest broadcast planting and or post-harvest drill planting. In each column, means followed by the same letter are not significantly different at α = .05. For nonsignificant interactions *P* values are given.

4 | CONCLUSIONS

We investigated the productivity of four cover crops established with two planting practices, in soybean–corn and corn–corn cropping sequences. To our knowledge, this is the first study that assesses effects of these factors on cover crop productivity and subsequently grown corn in the western Corn Belt. Our study spanned 4 yr and three sites, which made it possible to generalize inferences on cover crops and main crop interactions.

Our study provides management information on cover crop treatments and planting practices in soybean–corn and corn–corn sequences in the western Corn Belt and other regions with similar climates. Pre-harvest broadcast planting was more productive than post-harvest drill planting in sites with more fall precipitation. In drier sites, establishing cover crops by drilling post-harvest increases the potential for biomass production. Cereal rye had the most biomass and mixes were intermediate. Legumes had insignificant growth, regardless of planting practice, indicating they are not a good fit for these cropping systems. More applied research comparing different pre-harvest broadcast seeding times, cover crop species, cultivars within species, and combinations of species, will be crucial to increase the success of pre-harvest broadcast interseeded cover crops and advance their adoption. The influence of cropping system should be assessed more systematically, to find optimum species and planting times for corn vs. soybean systems.

Cereal rye and mixes had moderate N uptake which was sometimes reflected in soil nitrate reductions. Soil P, K, and soil organic C concentrations were less influenced by treatments. In the soybean–corn sequence, yield reductions after cereal rye and in the corn–corn sequence after pre-harvest planted cover crops occurred but were small. Cereal rye may be the most suited cover crop to reduce the potential for nitrate leaching, but other species and planting methods may result in neutral or even positive corn yield responses. Management practices that improve corn performance after cover crops need to be explored in more depth, considering site-specific cover crop goals and growing conditions.

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AUTHOR CONTRIBUTIONS

Katja Koehler-Cole: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Validation; Visualization; Writing – original draft; Writing – review & editing. **Roger W. Elmore**: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Validation; Writing – review & editing. **Humberto Blanco-Canqui**: Conceptualization; Funding acquisition; Validation; Writing – review & editing. **Charles A. Francis**: Conceptualization; Funding acquisition; Writing – review & editing. **Charles A. Shapiro**: Conceptualization; Funding acquisition; Resources; Writing – review & editing. **Christopher A. Proctor**: Conceptualization; Funding acquisition; Writing – review & editing. **Sabrina J. Ruis**: Resources; Validation; Writing – review & editing. **Suat Irmak**: Resources; Validation. Derek M. Heeren: Resources; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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