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Soil Fertility and Crop Nutrition

Summer legumes following winter wheat boost soil nitrogen availability and corn yield

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Abstract

Efficient nitrogen (N) management is critical for improving nitrogen use efficiency (NUE) and sustaining corn (*Zea mays* L.) yields. We evaluated summer cover crops planted after winter wheat (*Triticum aestivum* L.) to quantify biomass, N content, soil N dynamics, and subsequent corn performance under rainfed conditions in eastern Nebraska. Across 2 site-years (2020–2021 and 2023–2024), eight CC treatments were tested, including six legumes, one grass, one legume mixture, and two no-CC controls. Cover crop biomass ranged from 760 kg ha^{-1} (cereal rye (*Secale cereale* L.), Austrian winter pea (*Pisum sativum arvense* L.)) to 8630 kg ha^{-1} (sunn-hemp (*Crotalaria juncea* L.), legume mixture). Hairy vetch (*Vicia villosa* L.) and soybean (*Glycine max* (L.) Merr.) had high biomass N accumulation (176 and 188 kg N ha^{-1}, respectively) due to biological N-fixation. Hairy vetch significantly increased soil nitrate-N availability by 154% (preplant) and 111% (in-season) compared to the no-N and cereal rye controls. Corn yield improved significantly ($p < 0.001$) following legume CCs, with hairy vetch, sunn-hemp, and forage-pea (*Pisum sativum* L.) outperforming other species. Legumes increased corn yield by 2.50 Mg ha^{-1} (2021) and 2.23 Mg ha^{-1} (2024) compared to the N control treatment, contributing 29 and 44 kg ha^{-1} of grain N, respectively. Apparent N credits from legumes ranged from 32 to 99 kg N ha^{-1}. In contrast, cereal rye reduced yield and N uptake, indicating net N immobilization. These results support legume CCs as a viable strategy to enhance NUE in rainfed corn systems.

Plain Language Summary

Corn production often depends on nitrogen fertilizer but using too much can pollute water and harm the environment. Planting cover crops between main crops can improve soil health and reduce the need for fertilizer. This study looked at how different summer cover crops grown after wheat affect soil nitrogen, corn yield, and fertilizer use. Legume cover crops like hairy vetch and sunn hemp added more nitrogen

Abbreviations: AE, agronomic efficiency; ANC, apparent nitrogen credit; C:N, carbon-to-nitrogen; CC, cover crop; NDRE, normalized difference red edge.

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to the soil than grasses and helped corn grow better, boosting yields by over 2 Megagram per hectare compared to no cover crop. In contrast, grasses like cereal rye lowered both soil nitrogen and corn yield. The results show that legume cover crops after wheat can reduce fertilizer needs by up to 99 kg of nitrogen per hectare while maintaining or improving corn production. This approach can help farmers save money and protect water quality by reducing nitrogen losses to the environment.

1 | INTRODUCTION

In the temperate US Corn (*Zea mays* L.) Belt, the adoption of winter cover crops (CCs) has often been promoted as a conservation strategy aimed at improving soil health, reducing nutrient losses, and delivering a suite of agroecosystem services (Blanco-Canqui et al., 2015; Schipanski et al., 2014; Van Eerd et al., 2023). These include erosion control, improved soil structure, enhanced biological activity, and nutrient retention (Dabney et al., 2001; Haruna & Nkongolo, 2015; Kaspar & Bakker, 2015; Ruan et al., 2001). In addition, winter CCs can suppress weeds (Florence et al., 2019), improve soil organic carbon (SOC) stock (Lal, 2015), and provide ecological soil nutrient management to chemical approaches (Perrone et al., 2022). However, despite widespread advocacy, the actual performance of winter CCs has been inconsistent and site-specific, particularly under rainfed cropping systems common in Nebraska. Multiple studies have documented the limitations of winter CCs in achieving their intended benefits. For example, Oliveira et al. (2019) reported frequent failures in stand establishment, particularly in years with delayed fall planting or early onset of cold temperatures. Inadequate biomass production due to short growing windows, harsh winter conditions, temperature variability, and unpredictable snowfall is a common issue, which ultimately limits nutrient uptake and soil coverage. Barker et al. (2018) noted that winter CCs often have negligible effects on soil water storage, which can be critical for early-season crop growth in water-limited environments. Furthermore, their impact on subsequent crop yields, especially corn, tends to be variable and modest. Marcillo and Miguez (2017) found that winter CCs in corn–soybean [*Glycine max* L. (Merr)] systems led to yield effects ranging from neutral to slightly positive, with outcomes often depending on species selection, termination timing, and spring weather conditions. Another multi-year study from southern Wisconsin found that cover cropping under corn–soybean rotation system require adjustment to address corn yield decline, while winter wheat (*Triticum aestivum* L.) provided an opportunity to integrate CCs in the system (Malone et al., 2022).

Adoption challenges are especially pronounced among small-scale growers. A statewide survey conducted in Nebraska in 2017 revealed that logistical barriers such as timely planting after harvest and spring termination without affecting corn planting schedules were key obstacles limiting winter CC adoption (Oliveira et al., 2019). These challenges are magnified in continuous corn or corn–soybean rotations, where narrow windows between harvest and freezing temperatures significantly restrict fall establishment. Ruis et al. (2017) and Koehler-Cole et al. (2020) highlighted that this short establishment window leads to reduced biomass and poor N scavenging capacity, thereby diminishing the overall agronomic and environmental returns of winter CCs. In turn, these limitations reduce growers' confidence and motivation to invest in CC management.

Recent shifts in cropping patterns and climate trends, however, have opened new opportunities to explore alternative cover cropping windows in the region. Notably, the wheat-growing area in Nebraska increased by 10.84% in 2024 compared to the 2020 harvested acreage (USDA NASS, 2025). While wheat production has traditionally been concentrated in western Nebraska, there is growing interest in integrating winter wheat into rainfed and limited-irrigation systems in eastern Nebraska (Baenziger et al., 2020). This shift is driven by the adaptability of wheat to drier spring conditions and its potential to diversify cropping systems. Importantly, wheat is harvested in mid-summer—usually by early July—which opens a ~90-day fallow window before winter sets in. Following winter-wheat harvest, there exists a distinct but often overlooked opportunity to grow summer CCs that efficiently use residual soil moisture and nutrients.

One key concern in post-wheat fallow systems is N loss through nitrate leaching (Campbell et al., 1984; Thomas et al., 2017). During the fallow period between wheat harvest and the following crop, soil temperatures often remain above 50°F, a range conducive to microbial activity and N mineralization. In the absence of living crop roots, residual N—especially in the form of nitrate (NO_3—N)—accumulates in the soil profile and becomes vulnerable to leaching during winter and early spring (Rutan & Steinke, 2019). The incorporation of summer CCs immediately after wheat harvest can help mitigate these losses by taking up residual N, thereby reducing environmental risks and contributing to long-term soil fertility.

Among summer CC options, non-legumes like winter cereal rye (*Cereal secale L.*), oat (*Avena sativa* L.), and

sorghum-sudangrass (*Sorghum bicolor* × *Sorghum bicolor var. sudanese*) have traditionally been used due to their rapid growth and high biomass potential. These species are effective nitrate scavengers (Chim et al., 2022; Vyn et al., 2000), but their contributions to subsequent N availability are limited. Their high carbon-to-nitrogen (C:N) ratios often lead to N immobilization during decomposition, which can suppress N availability to the following corn crop, especially in low-input systems. Conversely, legume cover crops—such as cowpea (*Vigna ungiculata* L.), sunn hemp (*Crotalaria juncea* L.), and mung bean (*Vigna radiata* L.)—present a promising alternative due to their ability to fix atmospheric N and their generally lower C:N ratios. These traits not only enhance N availability for the subsequent crop but also improve soil structure, increase microbial enzyme activity, solubilize unsolvable soil phosphorus, and promote better soil aggregation (Kebede, 2021; N'Dayegamiye et al., 2015; Stagnari et al., 2017). Previous studies have successfully reported the greatest SOC and crop yield benefits from legume CCs under low N fertilization and low initial SOC stock conditions (He et al., 2025). Further, nitrogen fixation from legume CCs decreases with an increase in soil available N concentration (Alon et al., 2021; Hoorman & Sundermeier, 2017; Kebede, 2021). Several studies have documented increased corn grain yield following legume CCs, particularly when their biomass is well established and decomposes under favorable soil conditions (Blanco-Canqui et al., 2012; Yang et al., 2023a). Importantly, legume CCs have also demonstrated the capacity to maintain yields comparable to those achieved with conventional fertilizer rates in systems transitioning to organic production (X. M. Yang et al., 2019).

Despite this potential, there remains a significant knowledge gap regarding the use of summer legume CCs following winter wheat in Nebraska. Most research to date has focused on winter CCs or summer CCs in vegetable systems, with limited exploration of their role in large-scale grain production systems. Adoption in these systems has been minimal, likely due to logistical challenges and a lack of region-specific data. Specifically, little is known about how legume species perform in the summer window after wheat, how much N they contribute to the following corn crop, and how N fertilizer rates should be adjusted to account for this contribution. Without this knowledge, growers are hesitant to reduce fertilizer inputs, limiting the potential for both economic and environmental benefits.

To address these gaps, we conducted a field study in eastern Nebraska using soybean-winter wheat/cover crop–corn rotation. This rotation not only fits well within existing cropping systems but also allows for the integration of summer CCs between wheat harvest and corn planting. The study was designed to evaluate the performance of different CC species—both legumes and non-legumes—during the summer period, with a focus on their effects on biomass production, N accumulation, and soil N dynamics. By tracking seasonal changes in soil N concentration and assessing subsequent corn growth and yield, we aimed to generate practical, region-specific recommendations for integrating CCs into wheat-corn systems.

Core Ideas

- Summer cover crops (CCs) after winter wheat improved CC biomass and nitrogen accumulation.
- Legume CCs improved soil nitrate N availability by up to 154% over zero nitrogen control treatment.
- Corn yield following legume CCs was 2 Mg ha^{-1} more compared to corn under no CCs.
- Legume CCs provided nitrogen credits ranging from 32 to 99 kg N ha^{-1}, reducing nitrogen fertilizer needs.
- Winter cereal rye reduced corn yield and nitrogen uptake due to nitrogen immobilization.

The specific objectives of this study were to (i) evaluate the impact of different summer CC species on biomass production and N availability and (ii) compare the seasonal N dynamics and subsequent effects on corn growth and yield across species. We hypothesized that legume CCs would fix atmospheric N and, upon termination, contribute N to the soil through mineralization, and different CC species would enhance in-season N availability, thereby positively influencing corn growth and grain yield under reduced synthetic N input conditions.

2 | MATERIALS AND METHODS

2.1 | Site description

This study was conducted at Rogers Memorial Farm, University of Nebraska-Lincoln, Lincoln, Nebraska (40.84°N, 96.46°W) during the 2020/21 and 2023/24 growing seasons under the corn phase of a three-phase crop rotation (winter wheat/cover crop-corn-soybean). The year 2022, corresponding to the soybean phase, was excluded from the study, as the focus was on corn following winter wheat. Accordingly, measurements were conducted in 2023 for aboveground CC biomass and tissue N and in 2021 and 2024 for corn grain yield and associated crop variables.

The site has been under a no-till management system since 1991, with three crop rotations starting with wheat in 2007. CCs were first introduced in 2011, drilled into wheat stubble,

TABLE 1 Basic soil physicochemical properties prior to fertilizer application in 2024.

Parameters	Values*
Soil pH	6.8
Electrical conductivity (dS/m)	0.05
Soil organic matter (LOI g kg^{-1} soil)	37
Ammonium-N (mg N kg^{-1} soil)	4.8
Nitrate-N (mg N kg^{-1} soil)	5.0
Potassium (mg K kg^{-1} soil)	265.6
Phosphorus (Mehlich-III mg P kg^{-1} soil)	21.6
CEC/sum of cations (cmol kg^{-1} soil)	18.3

Abbreviations CEC, cation exchange capacity; LOI, loss on ignition.
*Values represent means of three replications in control plots without cover crops and nitrogen fertilizer.

followed by corn production in 2012. The soil at the site is classified as Aksarben silty clay loam (fine, smectitic, mesic Typic Argiudolls), with a slope ranging from 2% to 11% (Soil Survey Staff, 2022). The field has been managed under a rain-fed cropping system since 1992. The basic physical and chemical properties of the soil prior to fertilizer application in 2021 were not available; however, the properties measured prior to the 2024 fertilizer application are presented in Table 1.

2.2 | Experimental design and treatment details

The field trial was established using a randomized complete block design for both study years (Figure 1). Treatment consisted of diverse legume CC species, cereal rye, and two controls (N with no cover and no N with no cover [N_0]). The mixture comprised five legume species selected for the study. All 10 treatments were randomized in three replications with a total of 30 plots under study. The details of treatments and CC seeding rates in the years 2020/21 and 2023/24 are presented in Table 2. The plots were 9.1 m wide and 73.1 to 118.8 m long, depending on the field availability. CCs were seeded after winter wheat harvest on July 19, 2020, and July 21, 2023, except for cereal rye and Austrian winter pea, which were drilled on September 15, 2020, and September 1, 2023. CCs were drilled at row spacing of 19 cm with CrustBuster (Model 4615-24) planter. Cereal rye and Austrian WP were planted late to avoid high temperature (>30°C) affecting their germination and establishment due to increased seedling mortality (Brar et al., 1991; Butler et al., 2017). CCs were winter-killed except for cereal rye, Austrian WP, and hairy vetch, which were terminated on April 11, 2021, and April 9, 2024, with mixture of residual and contact herbicide (Corvus, atrazine, 2,4-D, and glyphosate) a week before fertilizer application and 2 weeks before corn planting. Urea ammonium nitrate (UAN-28%) was injected at 6.35-cm depth and 19.05 cm spacing at the rate of 56.68 kg N ha^{-1} in all CC treatments and N control except N_0 control. This relatively low N rate, compared with typical recommendations for rainfed corn in Nebraska, was selected to better quantify the N contribution from legume-based CCs. Corn was planted on April 28 and April 23 in 2021 and 2023 with 6-row Case IH 955 planter for both years. Corn hybrid planted was Dekalb (DKC62-00RIB AR2 VT3P), maintaining a plant population of 80,000 ha^{-1}. Corn was harvested for grain yield on October 8 with Gleaner R55 combine harvester for both years.

2.3 | CC sampling and analysis

Aboveground CC biomass was sampled for estimating biomass accumulation and N concentration only in the second year of study. Biomass sampling was carried out on October 27, 2023, before the onset of winter, approximately 57 and 99 days after two different CC drilling dates. Cereal rye, Austrian WP, and hairy vetch were still accumulating biomass during spring before termination. Two random samples per plot covering 0.5 m^2 area were clipped using scissors, which were air-dried at 60°C for a week and weighed to obtain CC biomass production. A sub-sample of each plot was sent for nutritive value analysis in the commercial laboratory (Ward Laboratory) to assess carbon and N concentrations and C:N ratio of CC residue. Based on the nutritive value results, biomass N content was estimated with Equation (1).

$$\text{Biomass N content } \left(\text{kg ha}^{-1}\right) = \frac{\text{Cover crop N concentration } (\%) \times \text{ Biomass } \left(\text{kg ha}^{-1}\right)}{100} \quad (1)$$

2.4 | Soil sampling and analysis

Soil samples were collected from N_0 (no nitrogen) control plots on March 22, 2024, at a 0- to 20-cm depth from each replication to determine basic soil properties. During the second year of the corn phase (2024), in-season soil sampling was conducted at multiple corn growth stages to evaluate the effects of CCs on soil inorganic N concentration. Following fertilization, in-season soil samples were taken monthly from April through July at a 0- to 15-cm depth. Each sample consisted of four soil cores per plot, collected while avoiding UAN band locations to accurately capture N dynamics. The samples were transferred to a cooler and transported to the laboratory for extraction and analysis. For soil extraction, 50 mL of 2 M KCl was added to the samples, and the solution was shaken horizontally at 180 rpm for 1 hour as described in

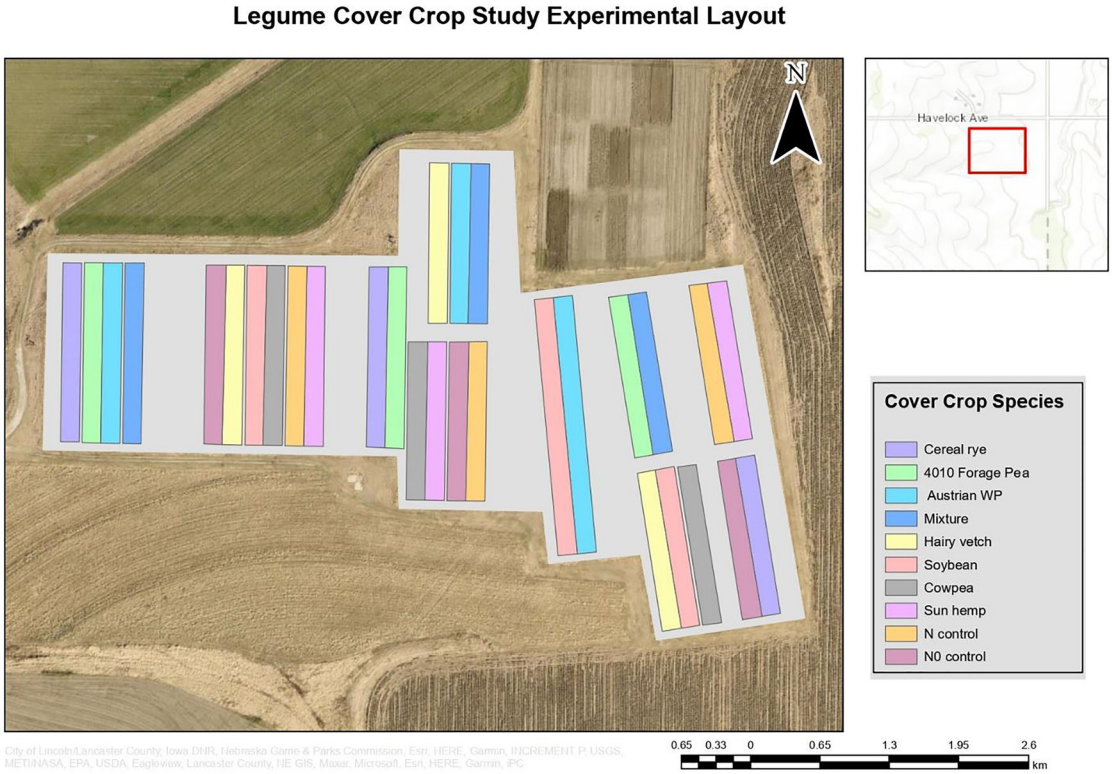


FIGURE 1 Treatment layout at Rogers Memorial Farm, Lincoln, NE, during 2020–2021 and 2023–2024. Chickling vetch was replaced with 4010 forage pea in 2023.

TABLE 2 Cover crop treatments and seeding rates used in the 2020 and 2023 study years.

Treatment	Cover crop (CC) specie (s)	Seeding rate (kg ha^{-1})
1	Cereal rye (*Secale cereale* L.)	68.02
2	Chickling vetch (*Lathyrus sativus* L.)—2020	100.87
	4010 Forage pea (*Pisum sativum*)—2023	56.68
3	Austrian winter pea (*Pisum sativum* subsp. *arvense*)	68.02
4	Mixture	
	Chickling vetch—2020	17.93
	4010 Forage pea—2023	13.45
	b. Hairy vetch (*Vicia villosa* L.)	4.48
	c. Soybean [*Glycine max* (L.) Merr]	16.81
	d. Cowpea (*Vigna unguiculata* L.)	13.81
	e. Sunn hemp (*Crotalaria juncea* L.)	3.36
5	Hairy vetch	22.67
6	Soybean	68.02
7	Cowpea	56.68
8	Sunn hemp	17.00
9	N Control	–
10	N_0 Control	–

Note: Chickling vetch was replaced by 4010 Forage pea in 2023 due to seed unavailability.

Iqbal et al. (2015) and Neels et al. (2024a, 2024b). The suspension was then filtered through Whatman No. 1 filter paper, and the filtrate was collected in vials for analysis of soil ammonium (NH_4—N) and NO_3—N. The concentration of NH_4—N was determined using Berthelot reagents, while NO_3—N was quantified using Griess-Ilosvay reagents with vanadium chloride, both analyzed in microplates (Archontoulis et al., 2020).

Residual soil NH_4—N and NO_3—N were determined through deep core sampling conducted after the harvest of the main crop on October 21, 2024. Deep core soil sampling was performed using a Giddings hydraulic probe with a 4.19 cm diameter, reaching a depth of 1.2 m. Two deep cores were collected between crop rows and segmented by depth into 0–30, 30–60, 60–90, and 90–120 cm intervals. The segmented samples were subsequently analyzed for NH_4—N and NO_3—N concentrations at each depth, following the same analytical procedure used for in-season soil NH_4—N and NO_3—N analysis.

2.5 | Proximal sensing, crop sampling, and analysis

Assessment of N release and inorganic N availability from CC residue decomposition to cash crop was monitored with the help of vegetation indices using a handheld proximal sensor RapidSCAN CS-45 (Holland Scientific) during corn phase in 2024. The sensor uses three measurement channels: 670, 730, and 780 nm, which can estimate visible red, red edge, and near-infrared reflectance from crop canopy. The normalized difference red edge (NDRE) was collected from two central corn rows and averaged to find a mean value at different sampling dates. The measurements were taken at the sixth visible leaf collar stage—V6, V8, V12, and Silking-R1 corn growth stage, respectively. Previous studies have demonstrated a strong correlation between the NDRE index and corn grain yield. In this study, NDRE measurements taken at the V8 and V12 growth stages were utilized to develop a regression model for predicting corn grain yield. To estimate the stover biomass and nutrient content, six-plants hand harvest was carried out before combined harvest on September 27, 2024. Stover fresh weight was recorded, and a sub-sample was air-dried to estimate dry biomass. The dry sub-samples for each plot were sent for biomass nutritive value analysis, and the results were used for the following estimates.

$$\text{Harvest index (HI)} = \frac{\text{Grain yield}\left(\frac{\text{Mg}}{\text{ha}}\right)}{\text{Grain + stover yield}\left(\frac{\text{Mg}}{\text{ha}}\right)} \quad (2)$$

$$\text{Total N uptake (TNU kg N ha}^{-1}\text{)} = \left[\text{Grain N content} \times \text{grain dry matter}\left(\frac{\text{kg}}{\text{ha}}\right)\right] + \left[\text{Stover N content} \times \text{stover biomass in}\left(\frac{\text{kg}}{\text{ha}}\right)\right] \quad (3)$$

$$\text{Nitrogen harvest index (NHI\%)} = \frac{\text{Grain nitrogen uptake}\left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Total nitrogen uptake}\left(\frac{\text{kg}}{\text{ha}}\right)} \times 100 \quad (4)$$

$$\text{Apparent N credit (ANC, kg N ha}^{-1}\text{)} = \left[\text{Total corn N uptake in CC plot}\left(\frac{\text{kg}}{\text{ha}}\right) - \text{Total corn N uptake in N control plot}\left(\frac{\text{kg}}{\text{ha}}\right)\right] \quad (5)$$

$$\text{Agronomic efficiency (AE)} = \frac{\text{Grain yield in CC plot}\left(\frac{\text{kg}}{\text{ha}}\right) - \text{Grain yield in N0 control}\left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Total N applied}\left(\frac{\text{kg}}{\text{ha}}\right)} \quad (6)$$

2.6 | Statistical analysis

The datasets were analyzed using SAS (Version 9.4). Each data set was checked for normal distribution assumption with PROC UNIVARIATE procedure. PROC GLIMMIX procedure was used for the analysis of variance (ANOVA) for each parameter, and Fisher's least significant difference (LSD) test was used for the treatment mean comparison with Tukey's honestly significant difference (HSD) adjustment for control of Type-I error rate and better result reliability. In-season inorganic N and corn NDRE were analyzed using repeated-measures ANOVA with covariance structure compound symmetry. However, other parameters were analyzed for the treatment effects only. PROC CORR and PROC REG procedures were used for correlation and regression equation among the variables. Contrast analysis between legumes versus grass and mixture versus mono-species was achieved using ESTIMATE procedure.

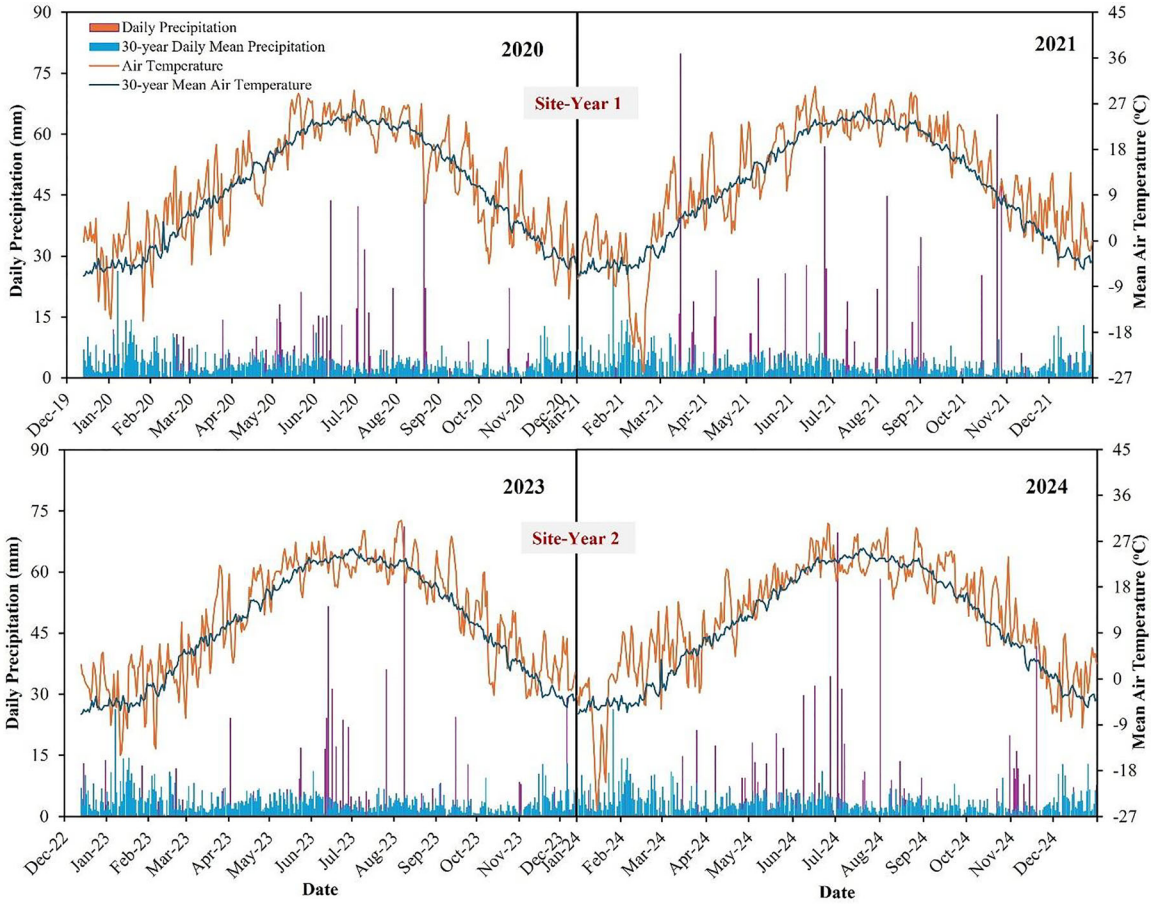


FIGURE 2 Daily precipitation (mm) and mean air temperature (˚C) during site-year 1 (2020–2021), site-year 2 (2023–2024), and the 30-year average at the study site. Purple and light blue bars indicate daily precipitation for each site-year and the 30-year average, respectively. Orange and dark blue lines represent corresponding mean air temperatures.

3 | RESULTS AND DISCUSSION

3.1 | Weather during study

3.1.1 | CC years: 2020 and 2023

In the CC years of 2020 and 2023, the site received 613 and 640 mm less total annual precipitation, respectively, than the 30-year mean (Table S1; Figure 2). Despite the annual deficit, rainfall during the CC growing period (July–October) was relatively favorable for growth. Site-year 1 (2020) received 310 mm (47% of annual precipitation), and site-year 2 (2023) received 384 mm (>60% of annual precipitation) during this period. Compared to the 30-year average precipitation for the same period (323 mm), rainfall was slightly lower in 2020 but higher in 2023. Mean air temperatures during the CC growing season were close to the 30-year average (19.20˚C), measuring 18.75˚C in 2020 and 20.06˚C in 2023. Monthly mean temperatures ranged from −2.89˚C (January) to 24.89˚C (July) in 2020 and −2.18˚C (January) to 23.61˚C (August) in 2023. The warm temperatures and adequate rainfall during the CC season supported strong establishment and high biomass production in both years.

3.1.2 | Corn years: 2021 and 2024

In the subsequent corn years, total annual precipitation was below the 30-year mean by 525 mm in 2021 and 479 mm in 2024 (Table S1; Figure 2). By contrast, corn-season (April–September) precipitation was 485 mm in 2021 and 542 mm in 2024; thus, 2021 was ∼100 mm below the 30-year corn-season average (585 mm), whereas 2024 was near average. Mean corn-season air temperatures were slightly above normal, averaging 19.85˚C in 2021 and 19.99˚C in 2024, approximately 1.00˚C and 1.14˚C higher than the 30-year average (18.85˚C). Monthly temperatures ranged from −9.30˚C (January) to 24.16˚C (August) in 2021 and −6.54˚C (January) to 23.85˚C (July) in 2024.

Despite the reduced total annual precipitation, the well-distributed rainfall during the early corn growing season, combined with optimal temperatures, enhanced early corn

TABLE 3 Cover crop biomass (kg ha^{-1}), biomass nitrogen content (kg N ha^{-1}), total carbon content (kg C ha^{-1}), and carbon-to-nitrogen (C:N) ratio as influenced by different cover crop species during 2023.

Treatments	Biomass (kg ha^{-1})	Nitrogen content (kg N ha^{-1})	Total carbon content (kg C ha^{-1})	C:N ratio
Cereal rye	780c	25.9c	340c	13.39c
4010 Forage pea	3210bc	74.2bc	1440bc	19.37bc
Austrian winter pea	740c	35.9c	350c	9.66c
Mixture	8600a	127.1ab	3890a	30.46ab
Hairy vetch	5300abc	176.6a	2370abc	13.52c
Soybean	6900ab	187.9a	3140ab	17.01bc
Cowpea	3400bc	69.7bc	1480bc	22.23abc
Sunn hemp	8670a	105.3b	3940a	36.24a
	Analysis of variance ($p < 0.05$)			
Treatments	0.0001***	<0.0001***	0.0002***	0.0001***
Legumes vs. grass	0.0025**	<0.0001***	0.0030**	0.0587
Mixture vs. mono	0.0009***	0.0573	0.0010**	0.0017**

Note: Treatment means followed by same letter (s) within column are not significantly different from each other based on Tukey HSD 0.05.
*, **, and ***Indicate significant differences at the $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.
Abbreviation: C:N, carbon to nitrogen ratio.

development under rainfed conditions. Additionally, these conditions supported rapid decomposition of CC residues, facilitating timely N release into the soil to support corn growth.

3.2 | Effects of CC species on biomass and nitrogen content

CC species had a significant influence on both biomass accumulation ($p < 0.001$) and N content prior ($p < 0.001$) to winter in 2023 (Table 3). Biomass production varied widely among species, primarily due to differences in growth characteristics, length of the growing period, and species-specific growth habits. Among the treatments, sunn hemp and the mixture (five legume species) produced the highest biomass, averaging 8630 kg ha^{-1}. In contrast, cereal rye and Austrian winter pea (WP) produced the least biomass, averaging only 760 kg ha^{-1}. The low biomass in cereal rye and Austrian WP was largely due to their shorter growing period (57 days) compared to the other CC species (99 days), resulting in 42 fewer days for photosynthesis and biomass accumulation. This difference is closely associated with lower growing degree days accumulation during the fall period, as reported in previous studies (Balkcom et al., 2011; Björkman et al., 2015). In addition, cereal rye's slow growth characteristics and Austrian WP's poor field establishment further limited their biomass production (Silva, 2014). Conversely, sunn hemp's rapid growth allowed it to accumulate substantial biomass within an 8–12-week frost-free period (USDA NRCS, 1999; Zegada-Lizarazu et al., 2024). The high biomass observed in the legume mixture was primarily due to sunn hemp's dominance within the mixture.

Interestingly, while sunn hemp and mixture produced the most biomass, greater biomass N content was observed in soybean and hairy vetch species (Table 3). Hairy vetch and soybean, excluding the mixture, showed significantly ($p < 0.001$) greater biomass N content than all other species. The greater N content in soybean and hairy vetch can be attributed to their excellent biological N fixation ability and quick-growing characteristics. In hairy vetch, up to 75% of its tissue N content can come from atmospheric N_2 fixation (Parvin et al., 2022; Perrone et al., 2020), a similar mechanism likely presents in soybean. In contrast, cereal rye and Austrian WP exhibited the lowest biomass N content, reflecting both their lower biomass production and lower tissue N concentration, particularly in cereal rye (Hargrove, 1986). On average, hairy vetch and soybean accumulated 151 kg N ha^{-1} higher than cereal rye and Austrian WP combined. This agrees with earlier studies reporting hairy vetch N accumulation between 149 and 211 kg ha^{-1} (Clark et al., 1995; Perrone et al., 2020).

A significant linear relationship was observed between CC biomass and N content, with a high coefficient of determination ($R^2 = 0.69$; $p < 0.001$) (Figure 4). This indicates that approximately 69% of the variability in biomass N content could be explained by biomass accumulation alone, suggesting that increasing biomass through species selection enhances N content via both residual soil N uptake and biological fixation (Sunoj et al., 2021; Yuan et al., 2019).

CC species also showed significant differences in their C:N ratios (Table 3). Hairy vetch and soybean had lower C:N ratios ($p < 0.001$), supporting their higher biomass N content despite lower total biomass production. In contrast, sunn hemp and mixture exhibited higher C:N ratios due to a greater stem proportion in their biomass. The higher biomass C:N ratio (>20:1) might have immobilized N during residue decom-

TABLE 4 Preplant and in-season soil nitrate N and ammonium N concentrations before and after nitrogen fertilization as influenced by cover crop treatments in 2024.

Treatments	Preplant		In-season	
	NO_3—N (mg kg^{-1} soil)	NH_4—N (mg kg^{-1} soil)	NO_3—N (mg kg^{-1} soil)	NH_4—N (mg kg^{-1} soil)
Cereal rye	1.08c	1.36	6.24dc	1.33
4010 FP	9.74ab	1.17	9.04bc	1.16
Austrian WP	12.00ab	1.10	10.81ab	1.23
Mixture	8.76ab	1.18	9.35bdc	1.13
Hairy vetch	14.50a	1.19	13.18a	1.26
Soybean	7.18bc	1.02	9.99ab	1.32
Cowpea	7.81abc	1.31	10.08ab	1.30
Sunn hemp	11.16ab	1.19	10.63ab	1.21
N_0 control	5.00c	1.18	5.17d	1.28
Date				
April 19, 2024	–	–	8.49b	1.17
May 23, 2024	–	–	20.44a	1.23
June 21, 2024	–	–	7.88b	1.29
July 19, 2024	–	–	0.73c	1.28
	Analysis of variance ($p < 0.05$)			
Treatments	0.0002***	0.1469	<0.0001***	0.5543
Date	–	–	<0.0001***	0.2238
Treatments × date	–	–	<0.0001***	0.2025
Legumes vs. grass	<0.0001***	0.0262*	<0.0001***	0.3115
Mixture vs. mono	0.8392	0.9224	0.4026	0.1205
CC vs. N_0 control	–	–	<0.0001***	0.6440

Note: Treatment means followed by same letter (s) within column are not significantly different from each other based on Tukey HSD 0.05.
Abbreviations: 4010 FP - 4010 Forage Pea; Austrian WP, Austrian winter pea; CC, cover crops; N0 control, zero N control.
*, **, and ***Indicate significant differences at the $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

position (Mansoer et al., 1997). Cereal rye and Austrian WP showed lower C:N ratios due to their vegetative growth stage at termination, although C:N ratios can vary with species maturity (Cottney et al., 2022; Lawson et al., 2015).

3.3 | Preplant and in-season soil nitrogen availability

3.3.1 | Preplant soil ammonium N and nitrate N

Preplant soil NO_3—N and NH_4—N concentrations prior to fertilizer application are presented in Table 4. Results showed that CC species had a significant effect on soil NO_3—N concentration ($p < 0.001$), while NH_4—N levels remained unaffected. The greater NO_3—N levels observed under CC species, particularly legume species, were attributed to residue decomposition and net N mineralization following winter-killed CCs. Fertilizer application in late March occurred after this initial N release. Among treatments, hairy vetch exhibited the highest preplant NO_3—N concentration, followed by sunn hemp, legume mixture, Austrian WP, and 4010 forage pea. In contrast, cereal rye and the N_0 control showed the lowest NO_3—N concentration. On average, hairy vetch resulted in 2.9 times greater NO_3—N than the N_0 control and 13.4 times greater than cereal rye. These differences align with previous findings (Poffenbarger et al., 2015; Sainju et al., 2005; Sievers & Cook, 2018), where legume CCs accelerated N release due to higher biomass N concentration and better residue quality compared to grass species. Further, contrast between legumes and grass showed greater NO_3—N concentration ($p < 0.001$) under legume species compared to cereal rye. However, the contrast between legumes and grass showed significantly greater preplant NH_4—N concentration ($p = 0.026$) under cereal rye compared to all other legume species. This is likely due to the high C:N ratio and slower decomposition of cereal rye residue, which can lead to temporary N immobilization and accumulation of ammonium during early stages of mineralization.

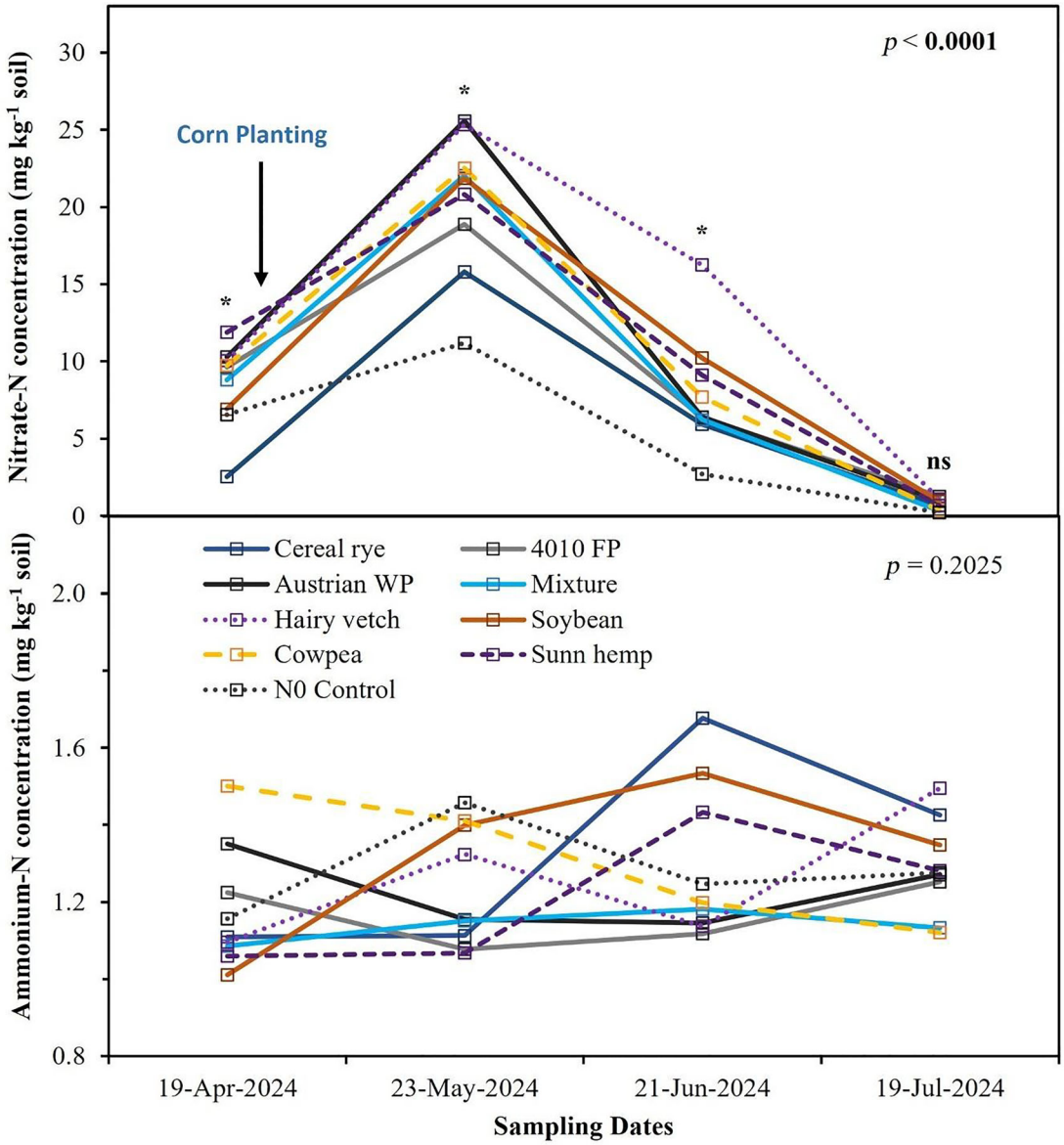


FIGURE 3 In-season soil nitrate N (upper) and ammonium N (lower) concentrations at different sampling dates as influenced by different cover crop species in 2024. Asterisks (*) indicate significant differences between treatment means at $p < 0.05$. 4010 FP, 4010 Forage Pea; Austrian WP, Austrian winter pea.

3.3.2 | In-season soil ammonium N and nitrate N

Throughout the growing season, in-season soil NO_3—N and NH_4—N dynamics were monitored monthly (Table 4; Figure 3). Repeated measures analysis showed that NO_3—N concentrations were significantly influenced by CC species ($p < 0.001$), sampling dates ($p < 0.001$), and their interaction ($p < 0.001$). Significant differences in NO_3—N availability among CC treatments were particularly evident in the first three sampling dates. Averaged across the entire growing season, hairy vetch consistently exhibited greater NO_3—N availability, followed by other legumes such as Austrian WP, soybean, cowpea, and sunn hemp. These results are consistent with past research (De Notaris et al., 2025; Kuo & Jellum, 2002; Zotarelli et al., 2009), which reported greater in-season soil NO_3—N availability following hairy vetch monoculture and the lowest levels under cereal rye. The lowest NO_3—N concentrations in this study were recorded in the N_0 control and cereal rye, likely due to low cereal rye biomass N content and slower residue decomposition.

Interestingly, despite a C:N ratio of <20:1 for cereal rye, similar to legumes, its decomposition and N release remained slower during the corn season, possibly due to poor residue quality and higher lignin content. Similar findings were reported by McKenney et al. (1995), who observed net N immobilization from cereal rye despite its low C:N ratio.

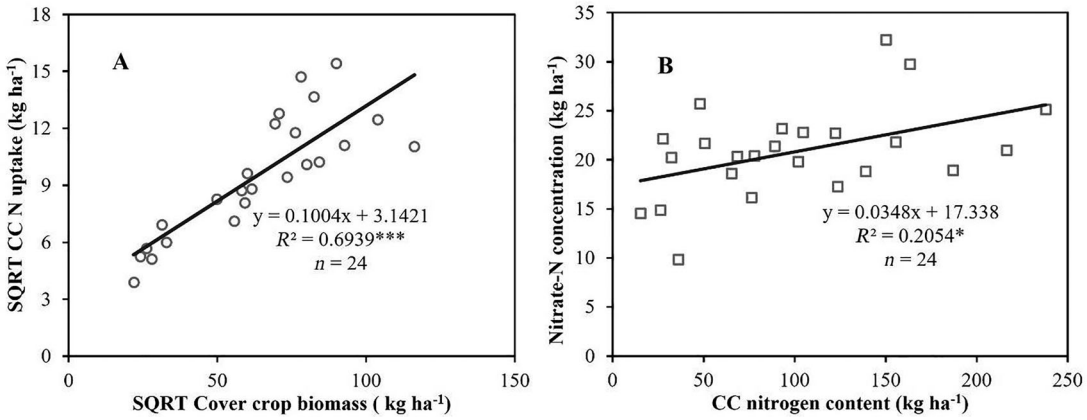


FIGURE 4 Linear regressions between the square root of cover crop biomass and cover crop biomass N in 2023 (A), and between cover crop biomass N and mean soil NO_3—N during the 2024 corn season (B). Asterisks (*, **, and ***) indicate significant differences at the $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

On average, hairy vetch improved in-season NO_3—N availability by 154% compared to the N_0 control and 111% compared to cereal rye. Contrasts revealed that CCs and legume species significantly ($p < 0.001$) increased soil NO_3—N availability by 90% and 70%, respectively, compared to the no-cover control and grass species. In contrast, in-season NH_4—N concentrations were not significantly ($p > 0.05$) influenced by CC species, sampling dates, or their interaction. All treatments exhibited similar NH_4—N levels throughout the season (Figure 3). This is likely due to rapid nitrification of NH_4—N to NO_3—N under warm soil temperatures (>50°F) and aerobic conditions, as supported by Li et al. (2013) and Greub and Roberts (2023). A regression analysis between CC biomass N content and average seasonal soil NO_3—N concentration revealed a significant linear relationship ($R^2 = 0.21$; $p = 0.026$) (Figure 4). This indicates that 20.5% of the variability in soil NO_3—N concentration was explained by CC biomass N content. Thus, greater biomass N content in legumes contributed to higher in-season soil NO_3—N availability, supporting corn N needs and aligning with findings from De Notaris et al. (2025).

3.4 | Crop vegetation index

The NDRE was significantly influenced by CC species, corn growth stage, and their interaction (Table 5; Figure 5). Across four growth stages, CC species showed significantly ($p < 0.001$) distinct effects on NDRE values. At the V6 stage, legume CCs like cowpea, hairy vetch, and Austrian WP had greater NDRE than the no-N control (N_0), while sunn hemp and cereal rye had values similar to N_0 control, possibly due to slower N mineralization. During V8 and V12 stages, all legumes showed greater NDRE than both N_0 control and cereal rye. At silking, mixture, hairy vetch, and sunn hemp produced the highest NDRE, indicating better N release from residues. Similarly, N_0 control consistently had the lowest NDRE which aligned with its lowest in-season soil NO_3—N concentration along with no additional N fertilization. Except for soybean, all legumes had higher NDRE than cereal rye and N0 ($p < 0.001$). NDRE peaked at V8, consistent with Teal et al. (2006), and higher NDRE at V8–V12 closely tracked greater grain yield, supporting canopy NDRE as a practical, in-season proxy for N sufficiency to inform additional N decisions.

3.5 | Corn yield and biomass

CC species influenced corn grain yield and HI but had no effect on stover biomass (Table 5). Corn grain yield was significantly influenced by CC species during both 2021 ($p < 0.001$) and 2024 ($p < 0.001$) growing seasons (Table 5; Figure 6). In 2021, corn yield was greater following CCs compared to both control treatments (with and without N fertilizer). Among the treatments, the highest grain yield was observed after hairy vetch, followed by sunn hemp, chickling vetch, mixture, and soybean. In contrast, the lowest yields were recorded in the N_0 control, followed by N control and cereal rye. Although CC biomass and N content were not measured in 2020, similar growth patterns were observed as in 2023, suggesting comparable effects on corn performance in 2021. On average, CC species and legume CCs increased corn grain yield by over 69% and 74%, respectively, compared to the combined controls. Additionally, CC species and legumes produced 2.23 and 2.49 Mg ha^{-1} higher grain yield compared to N control without CC. Based on a general conversion factor of 0.65 lbs. N bu^{-1} or 1.16% grain N concentration (Nafziger, 2023), this increase was equivalent to approximately 25.8 and

TABLE 5 Corn normalized difference red edge (NDRE), grain yield (Mg ha^{-1}), stover biomass (Mg ha^{-1}) and harvest index (HI) as influenced by different cover crop (CC) species in 2021 and 2024.

	2021	2024			
Treatments	**Grain yield (Mg ha^{-1})**	**NDRE**	**Grain yield (Mg ha^{-1})**	**Stover biomass**	**HI**
Cereal rye	7.33de	0.316c	8.68c	9.65	0.470c
Chickling vetch	9.48bc	–	–	–	–
4010 Forage pea	–	0.358ab	13.39a	10.00	0.548a
Austrian winter pea	7.90cde	0.355ab	12.77ab	10.52	0.532ab
Mixture	9.09bcd	0.353ab	12.62ab	11.40	0.540ab
Hairy vetch	12.08a	0.362a	13.95a	11.87	0.558a
Soybean	9.02bcd	0.352b	13.24ab	10.04	0.552a
Cowpea	7.87cde	0.357ab	13.27ab	10.23	0.567a
Sunn hemp	10.54ab	0.358ab	13.32a	10.61	0.537ab
N control	6.93e	0.305c	10.99bc	9.85	0.530abc
N_0 control	3.85f	–	9.75c	9.23	0.479bc
	Analysis of variance ($p < 0.05$)				
Treatments	<0.0001***	<0.0001***	<0.0001***	0.2565	0.0003***
Legumes vs. grass	<0.0001***	<0.0001***	<0.0001***	0.2321	<0.0001***
Mixture vs. mono	0.8314	0.6888	0.9431	0.1870	0.8883
CC vs. N control	<0.0001***	<0.0001***	0.0029**	0.3475	0.5638
CC vs. without CC	<0.0001***	–	<0.0001***	0.0789	0.0028**

Note: Treatment means followed by same letter (s) within column are not significantly different from each other based on Tukey HSD 0.05. Corn grain yields are expressed at 155 g kg^{-1} moisture level.

Abbreviation: N control, nitrogen receiving control without cover crop.

*, **, and ***Indicate significant differences at the $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

28.9 kg grain N ha^{-1} contributed by CC species and legumes, respectively, over the N control.

Similar trends were observed in 2024 (Table 5; Figure 6). All CCs except cereal rye significantly improved corn grain yield ($p < 0.001$). Hairy vetch, sunn hemp, and 4010 forage pea produced the highest yields, while soybean, cowpea, Austrian WP, and mixture resulted in intermediate yields, all significantly greater than cereal rye and N_0 control. Unlike 2021, cereal rye in 2024 produced the lowest yield, comparable to both control treatments. The greater corn yield following legume CCs in both years is likely attributed to an increase in-season mineral N availability from residue decomposition, which synchronized with corn N demand during active growth stage. This improved N availability enhanced corn vegetation index: NDRE values, indicating better N status and increased photosynthate partitioning to grain production. These findings align with previous studies reporting increased yield and soil N supply from legume CCs (Torbert et al., 1996; Vaughan et al., 2000; Vyn et al., 2000). Statistical analysis showed that CC species and legume CCs increased corn yield by >21% and 27%, respectively, over both controls combined in 2024. In terms of absolute yield, CC species and legumes produced 1.66 and 2.23 Mg ha^{-1} higher grain yield than the N control, corresponding to 34 and 44 kg grain N ha^{-1}, respectively.

Regression analysis indicated that corn yield in 2024 was positively correlated with CC biomass production and biomass N content (Figure 7). Biomass N content ($R^2 = 0.2668$; $p = 0.0097$) explained more variability in corn yield numerically than biomass alone ($R^2 = 0.1715$; $p = 0.044$), supporting previous findings (Ciampitti et al., 2012). However, Steiger's Z test and related methods indicated that this difference was not statistically significant ($p > 0.05$), suggesting both CC parameters may offer comparable predictive value for corn yield. Moreover, mean seasonal soil NO_3—N concentration ($R^2 = 0.6465$; $p < 0.001$) and NDRE values at V8-V12 ($R^2 = 0.7971$; $p < 0.001$) were strongly correlated with corn yield (Figure 7), further confirming the critical role of in-season N availability in determining yield potential (Preza-Fontes et al., 2020; Salardini et al., 1992).

Corn stover biomass in 2024 was not significantly affected by CC species (Table 5), with an overall mean of 10.34 Mg ha^{-1}. However, the HI differed among the treatments. The highest HI was observed following hairy vetch, soybean, cowpea, and 4010 FP, while the lowest HI was after cereal rye and N_0 control. These results suggest that legume CCs improved partitioning of aboveground biomass to grain yield without necessarily increasing total biomass. Similar observations were reported by Gifford et al. (1984) and more recently

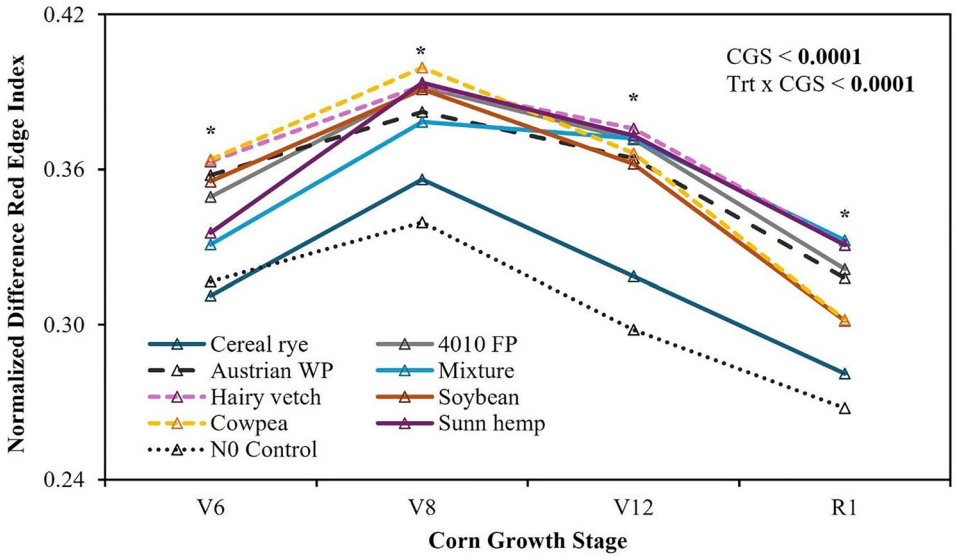


FIGURE 5 Normalized Difference Red Edge Index for cover crop (CC) species across corn growth stages in 2024. Asterisks (*) indicate significant differences at $p < 0.05$. CGS, corn growth stage; Trt, treatments; 4010 FP, 4010 forage pea; Austrian WP, Austrian winter pea.

by Cabello-Leiva et al. (2024), where legumes like faba bean (*Vicia faba* L.) increased HI compared to brassica species.

3.6 | Nitrogen uptake and nitrogen use efficiencies

CC species had a significant influence on corn N uptake in 2024 (Table 6). Total nitrogen uptake (grain + stover) was highest in hairy vetch, followed by cowpea, and lowest in cereal rye, N_0, and N control plots. Legume CCs improved total N uptake by 47% over the combined controls, adding an additional 55 kg N ha^{-1} compared to the N control without CCs. Previous studies have reported similar benefits, with increases in corn N uptake ranging from 65 to 130 kg N ha^{-1} with legume CCs (Holderbaum et al., 1990). In contrast, cereal rye reduced total N uptake by over 38% relative to the N control, emphasizing its potential to interfere with soil N availability for corn uptake, particularly when terminated late.

CC species also significantly influenced apparent nitrogen credit (ANC) and agronomic efficiency (AE) (Table 6). All CC species except cereal rye provided a positive ANC, with hairy vetch showing the highest contribution. Legume CCs provided an average ANC of 55 kg N ha^{-1} over the N control without CCs, equivalent to reducing synthetic N fertilizer use by the same amount. This aligns with past studies reporting N credits from legumes ranging between 39 and 100 kg N ha^{-1} (De Notaris et al., 2025; Gentry et al., 2013). X. Yang et al. (2023b) also reported N credit ranging 80–85 kg N ha^{-1} from legume species when planted after winter wheat in southwestern Ontario. Unlike legumes, cereal rye provided no N benefit and instead increased N fertilizer demand by 46 kg N ha^{-1} to achieve corn yields comparable to the N control. This is likely due to its low biomass N concentration and high C:N ratio, leading to microbial N immobilization during residue decomposition (Lupwayi et al., 2004; Williams et al., 2018).

The AE, defined as the additional grain yield produced per unit of applied N, was also maximized with legume CCs. Hairy vetch, soybean, cowpea, sunn hemp, and 4010 FP all achieved significantly higher AE than other treatments. Hairy vetch alone increased grain yield by 74 kg per kg of N applied compared to the N_0 control. In contrast, cereal rye resulted in the lowest AE, where 18 kg less grain was produced per kg of applied N compared to the N_0 control, highlighting its inefficiency without additional N fertilization. Integrating legume CCs enhanced grain production by 61 kg per kg of N applied on average and by 39 kg per kg of N applied compared to the N control without CCs. These findings reinforce the potential of legume CC species to offset N fertilizer needs while improving N use efficiency and sustainability in corn production systems.

3.7 | Residual soil nitrogen

Residual soil NH_4—N and nitrate N concentrations after corn harvest in late fall varied significantly with soil depth but were not significantly affected by CC treatments or their interaction with depth (Table S2; Figure 8). Across treatments, the mean soil NO_3—N and NH_4—N concentrations were 1.01 and 2.28 mg kg^{-1}, respectively. Contrast analysis showed that legume CCs had significantly higher residual soil NO_3—N concentrations by over 109% compared to grass species, while NH_4—N concentrations remained unaffected. These results

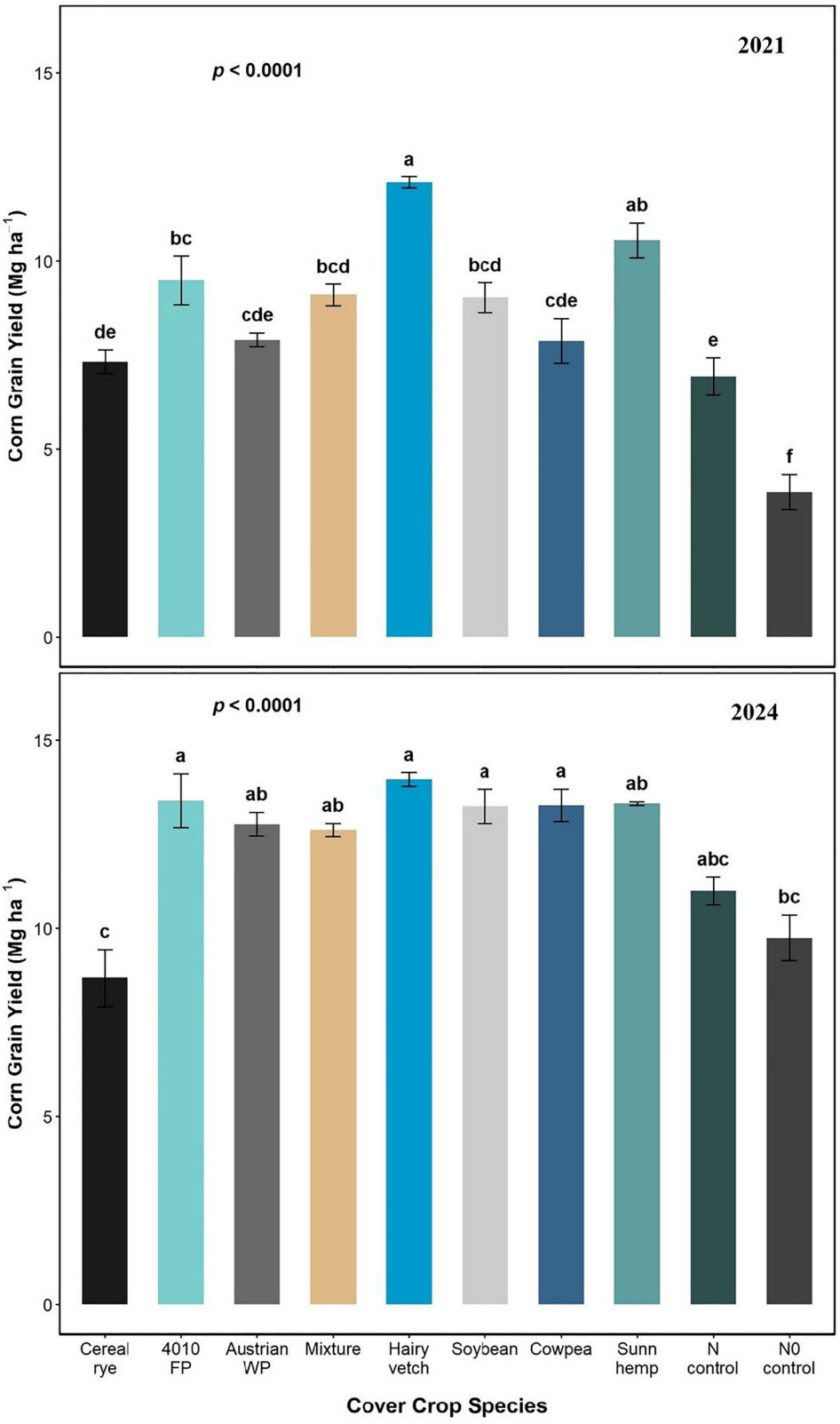


FIGURE 6 Corn grain yield as influenced by cover crop species in the years 2021 and 2024. Error bars represent the SE from mean. Different letters indicate significant differences between treatment means at $p < 0.05$. Chickling vetch was used in 2020 while it was replaced by 4010 FP in 2023.

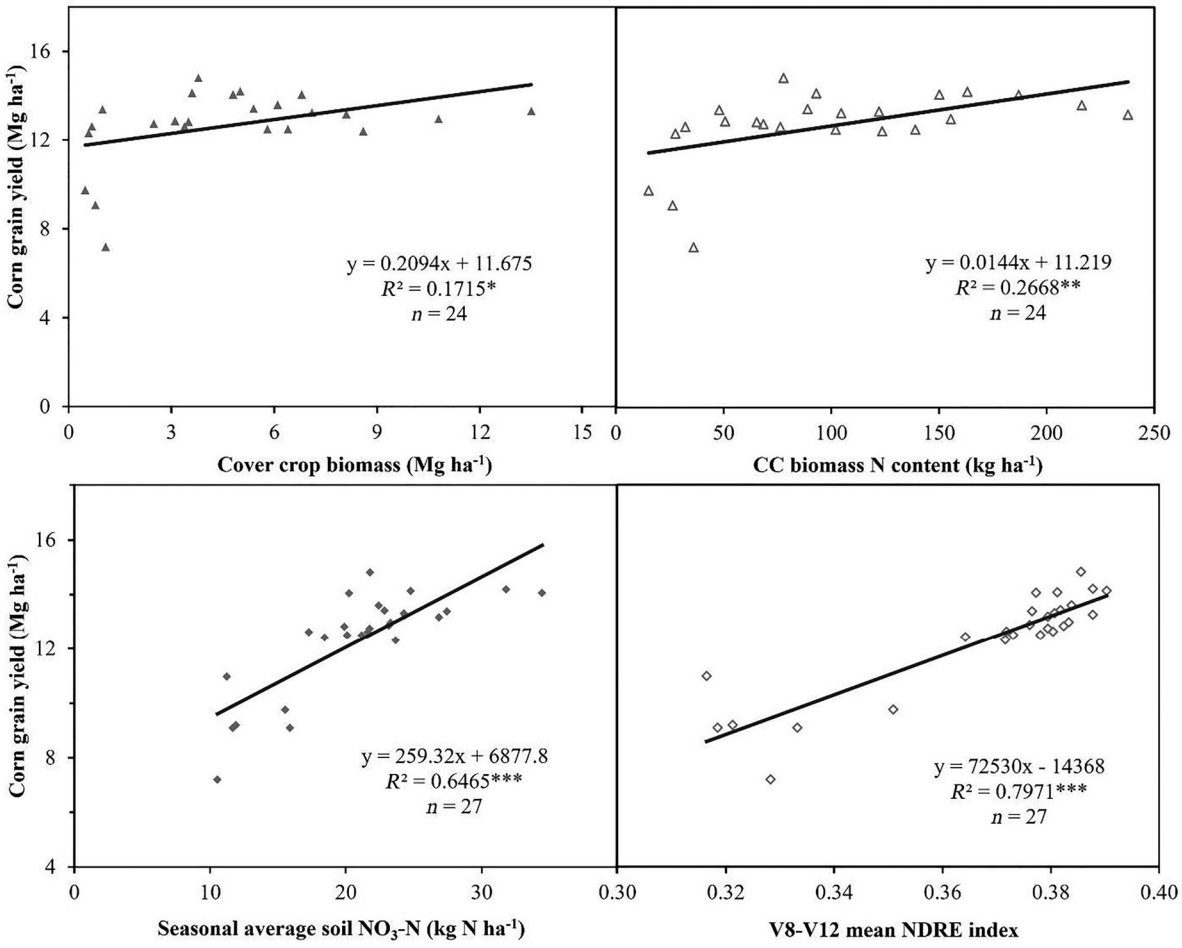


FIGURE 7 Linear regression between cover crop (CC) biomass, CC biomass nitrogen content, seasonal average soil NO_3-N, and V8-V12 mean normalized difference red edge (NDRE) with corn grain yield. Asterisks (*, **, and ***) indicate significant differences at the $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

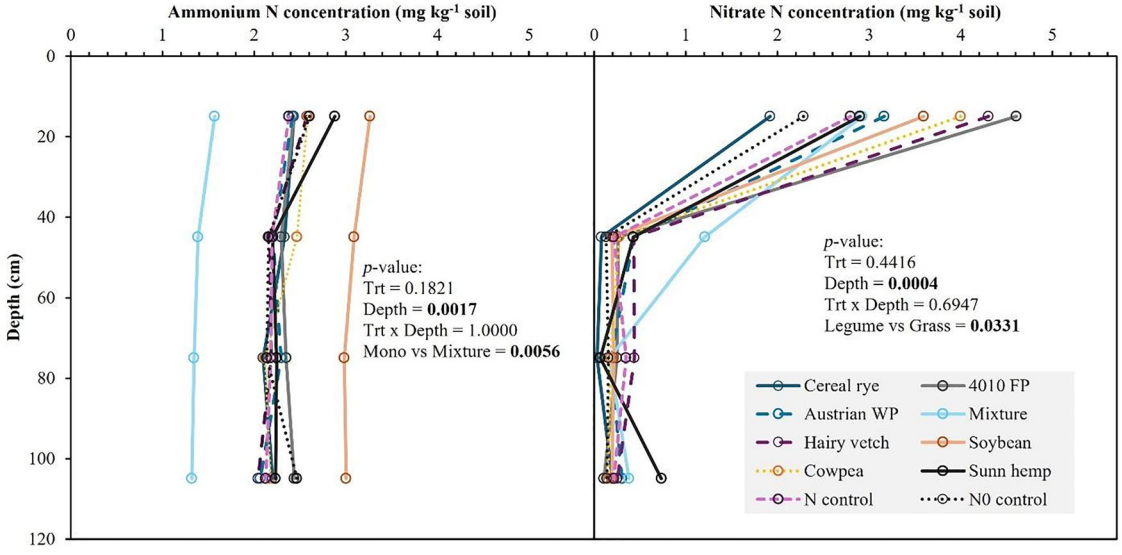


FIGURE 8 Residual soil ammonium-N and nitrate-N concentrations as influenced by cover crop species at various soil depths after corn harvest during fall 2024. Trt, treatments; Mono, mono cover crop species.

TABLE 6 Corn aboveground total nitrogen uptake (TNU), nitrogen harvest index (NHI), apparent nitrogen credit (ANC), and agronomic efficiency (AE) as influenced by different cover crop species in 2024.

Treatments	TNU (kg N ha^{-1})	NHI (%)	ANC (kg N ha^{-1})	AE (kg grain kg^{-1} N)
Cereal rye	121.04d	68.53b	−46.20c	−18.87c
4010 Forage pea	221.45abc	76.09ab	54.21ab	64.28a
Austrian winter pea	199.89bc	73.96ab	32.65b	53.33ab
Mixture	211.81abc	71.01ab	44.57ab	50.74ab
Hairy vetch	266.28a	69.68ab	99.04a	74.14a
Soybean	205.03bc	76.23ab	37.79b	61.60a
Cowpea	230.08ab	75.38ab	62.84ab	62.17a
Sunn hemp	221.85abc	77.68a	54.60ab	62.98a
N control	167.24 cd	72.11ab	–	21.87b
N_0 control	133.95d	70.03ab	–	–
	Analysis of variance ($p < 0.05$)			
Treatments	<0.0001***	0.0075**	<0.0001***	<0.0001***
Legumes vs. grass	<0.0001***	0.0024**	<0.0001***	<0.0001***
Mixture vs. mono	0.8452	0.1189	0.8502	0.9407
CC vs. N control	0.0024**	0.4220	–	0.0023**
CC vs. without CC	<0.0001***	0.0743	–	–

Note: Treatment means followed by same letter (s) within column are not significantly different from each other based on Tukey HSD 0.05.
Abbreviations: CC, cover crops; N control, nitrogen receiving control without cover crop.
*, **, and ***Indicate significant differences at the $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

were consistent with in-season soil N availability trends, where cereal rye maintained the lowest soil inorganic N levels. Cereal rye resulted in residual soil inorganic N level of <3 mg kg^{-1}, while legume species averaged slightly higher levels (<5 mg kg^{-1}). Similar trend of soil inorganic-N concentration (<3 mg kg^{-1}) with treatments including rye was reported by Kaye et al. (2019). Such low inorganic N levels, combined with low temperatures, limited soil moisture, and reduced microbial activity during fall and winter, suggest minimal potential for off-season nitrate leaching (Haan et al., 2017; Huggins et al., 2001; Singh et al., 2024, 2025). Interestingly, monoculture CC species had significantly higher residual NH_4—N concentrations compared to mixture species. This was likely due to the lower C:N ratio of legume residues in monocultures, promoting greater ammonium retention. Previous studies have reported similar findings (Jahanzad et al., 2016; Poffenbarger et al., 2015; Ranells & Wagger, 1996; Sievers & Cook, 2018).

As expected, both NO_3—N and NH_4—N concentrations were greatest in the upper soil depth (0–30 cm) and decreased with depth. Soil NO_3—N concentration in the surface layer was approximately 12 times greater than in lower depths, reflecting ongoing decomposition and mineralization of surface residues. Similarly, NH_4—N in the surface soil was 13% higher than the average of lower depths. Overall, this study highlights that while CC treatments did not significantly affect total soil inorganic N levels after harvest, legume species tended to maintain higher soil NO_3—N concentrations than grass species. These results emphasize the role of CC residue quality, especially C:N ratio, in influencing residual soil N availability and distribution within the soil profile following corn harvest.

4 | CONCLUSIONS

This field study demonstrated that integrating summer CC following winter wheat in eastern Nebraska has considerable potential to improve N management and sustain corn productivity in rainfed cropping systems. The results highlighted that CC species selection played a critical role in biomass accumulation, N content, soil N dynamics, and subsequent corn performance. Legume CC species, particularly hairy vetch, sunn hemp, cowpea, and forage pea, consistently enhanced soil nitrate-N availability, improved corn N uptake, and increased grain yield compared to non-legume species and no CC controls. The ANC provided by legumes ranged from 32 to 99 kg N ha^{-1}, indicating their potential to reduce synthetic N fertilizer requirements. In contrast, cereal rye demonstrated limited biomass and biomass N content, often reducing corn yield and N recovery due to increased N immobilization. Furthermore, this study found that legume CC species improved AE and nitrogen harvest index while maintaining low residual soil inorganic N after corn harvest, minimizing potential environmental losses. These findings provide regionally relevant evidence supporting the strategic

inclusion of summer legume CCs in wheat-corn rotations to enhance N cycling, reduce fertilizer dependency, and promote resilient, sustainable cropping systems in rainfed environments of eastern Nebraska. Corn producers are encouraged to consider legume CCs when seeking to reduce fertilizer inputs and improve soil nitrogen cycling in winter wheat–corn systems.

AUTHOR CONTRIBUTIONS

Madhusudhan Adhikari: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing—original draft. **Paul J. Jasa**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; validation; writing—review and editing. **Girma Birru**: Investigation; methodology; writing—review and editing. **Javed Iqbal**: C.onceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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