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Biomass and forage nutritive value of spring-planted cover crops in a semiarid region

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Abstract

Integrating cover crops (CCs) into cropping systems offers multiple benefits, including soil erosion control, nitrogen cycling, organic matter accumulation, weed suppression, and forage for livestock. Biomass, a key driver of these benefits, depends on species selection and adaptation to environmental conditions. In the western US's semiarid climate—characterized by cold, dry winters and short spring growing periods—CC options are limited due to winterkill risk and limited time between main crop cultivation. This study evaluated the biomass of 20 commercially available species, including grasses (seven), legumes (four), brassicas (three), and mixtures (six), grown from March to May at Sidney and Scottsbluff, Nebraska, in 2022 and 2023. At Sidney, Jerry oat (*Avena sativa* L.) had the greatest biomass (1.13 Mg ha^{-1}), exceeding other species by over 60%. At Scottsbluff, P919 barley (*Hordeum vulgare* L.) and a mixture of Lavina barley, 4010 pea (*Pisum sativum* L.), and Barsica rapeseed (*Brassica napus* L.) had the greatest biomass (0.71 Mg ha^{-1}). Grasses had 140% greater biomass than legumes and brassicas. Spring-planted CCs also had supplemental forage potential, with greater crude protein and total digestible nutrients, particularly in oat and barley. Growing degree days and precipitation explained 44% and 34% of biomass variation, respectively. All species had carbon-to-nitrogen ratios below 16. Despite lower biomass than reported thresholds, modest spring biomass of some species offers an alternative to winterkill or autumn planting constraints in semiarid systems. Results underscore the importance of selecting appropriate species suited to local conditions to maximize biomass and nutritive value.

1 | INTRODUCTION

The semiarid High Plains region often faces challenges to continuous cropping due to low precipitation and high evaporative potential (Jones & Popham, 1997). As a result, cash crops are often rotated with fallow periods to conserve soil moisture for subsequent crops (Hansen et al., 2012). However, precipitation storage efficiency during fallow periods is

Abbreviations: ADF, acid detergent fiber; CC, cover crop; CP, crude protein; GDD, growing degree day; NDF, neutral detergent fiber; NIRS, near-infrared reflectance spectroscopy; SOC, soil organic carbon; TDN, total digestible nutrients.

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limited, typically ranging from 10% to 35% (Plaza-Bonilla et al., 2015), and extended fallow periods contribute to soil degradation. This includes depletion of soil organic carbon (SOC) and nitrogen (N), erosion, and increased weed pressure (Peterson & Westfall, 2004; Sherrod et al., 2003).

Integrating cover crops (CCs) into cropping systems can shorten or replace fallow periods, improving soil health and productivity, even in semiarid regions (Rosenzweig et al., 2018; Sherrod et al., 2003). While autumn-planted CCs are commonly studied, spring planting offers an alternative window that can alleviate the time constraints associated with autumn harvest and planting season. During the autumn, planting CCs is often challenged by a narrow planting interval of only few weeks. If planting is delayed beyond this short period, there is a high risk of ground freezing with the onset of winter, leaving insufficient heat units for germination and increasing the likelihood of failed establishment. For example, a study reported that winter rye (*Secale cereale* L.) planted between September 15 and September 30 achieved maximum biomass (Chatterjee et al., 2020), while planting beyond October 5 left insufficient heat units for establishment (Wilson et al., 2013). Moreover, winter CCs frequently fail to survive harsh winters. Despite these challenges associated with autumn planting, spring-planted CCs remain relatively underexplored largely due to the short growing period.

The magnitude of ecosystem service benefits provided by CCs is closely linked to their biomass (Finney et al., 2016). A meta-analysis in the US Midwest reported that a minimum biomass of 5.0 Mg ha^{-1} is required to reduce weed biomass by up to 75% (Nichols et al., 2020), and a 0.5–1 Mg ha^{-1} threshold is needed for soil nitrate reduction (Hively et al., 2009; Thapa et al., 2018). Other studies indicate that at least 5.0 Mg ha^{-1} of residue or even more (6.8–7.6 Mg ha^{-1} year^{-1}) is necessary to maintain SOC in hot, dry agroecosystems (B. Ghimire et al., 2017; Halvorson & Schlegel, 2012). However, the lack of short-term economic returns from CCs often limits their adoption (Roesch-McNally et al., 2017). Utilizing CCs as a forage source offers an opportunity to generate immediate economic benefits while simultaneously improving soil ecosystem services (Schomberg et al., 2014; Siri-Prieto et al., 2009). Small grain cereals such as rye, triticale (×*Triticosecale* Wittm.), oat (*Avena sativa* L.), and barley (*Hordeum vulgare* L.) can accumulate satisfactory biomass (2.1–6.0 Mg ha^{-1}) and serve as high-quality forage, reducing reliance on perennial forage sources (Acharya et al., 2023; Landry et al., 2019). When grown alone or in mixtures with legumes or brassicas, these species have superior nutritive value (Acharya et al., 2023; Deen et al., 2019). Biomass, however, depends on various factors, including species selection, climate, soil characteristics, and management practices (Koehler-Cole et al., 2020; Ruis et al., 2019). Biomass can also vary within the same species due to differences in plant hardiness zones or local landscape features (Alizadeh et al., 2022).

Core Ideas

- Twenty spring-planted cover crop species were assessed for their biomass.
- Jerry oat had at least 33% greater biomass than other species.
- Growing degree days and precipitation explained 44% and 34% of biomass variation, respectively.
- All cover crop species had carbon-to-nitrogen ratios below 16.
- Oat and barley are forage options with superior nutritive value.

Despite known benefits, CC adoption remains limited in semiarid and arid regions globally. According to the 2022 agricultural census, less than 5% of total cropland acres in semiarid western Nebraska were planted with CCs, compared to over 10% in the region with greater rainfall in eastern districts (USDA-ERS, 2022). A recent survey examining producers' challenges and perspectives further revealed that adoption is higher in eastern Nebraska, where annual precipitation exceeds 711 mm, compared to less than 450 mm in the west (Das et al., 2022). Similar patterns of reduced adoption in other semiarid environments, such as parts of the US Great Plains, Australian drylands, and Mediterranean regions, have also been reported (R. Ghimire et al., 2018; Guo et al., 2024; Nordblom et al., 2023). Barriers include perceived or reported negative effects on cash crops due to water use, particularly when termination is delayed, and insufficient biomass to generate expected benefits (Nielsen et al., 2015; Rosa, Creech, Elmore, Rudnick, Lindquist, Fudolig, et al., 2021).

Among several factors, proper species selection can minimize soil water use and mitigate or reduce yield penalties. A study from semiarid western Nebraska reported that spring oats did not reduce corn (*Zea mays* L.) grain yield compared to fallow, indicating it as a promising option for these areas (Rosa, Creech, Elmore, Rudnick, Lindquist, Butts, et al., 2021). Another study reported that spring-planted CCs grown singly or in mixtures can accumulate biomass, with potential utility for grazing or harvest (Nielsen et al., 2015). While these studies provide valuable insights, there is a lack of species-specific biomass data for diverse CCs under western Nebraska's unique environmental constraints. Unless a broader range of options tailored to semiarid environments is made available, efforts to expand CC adoption in the region are likely to remain largely ineffective.

To address this gap, this study evaluated the biomass of 20 spring-planted CCs, including grasses, legumes, brassicas, and their mixtures, at two sites in the Nebraska Panhandle.

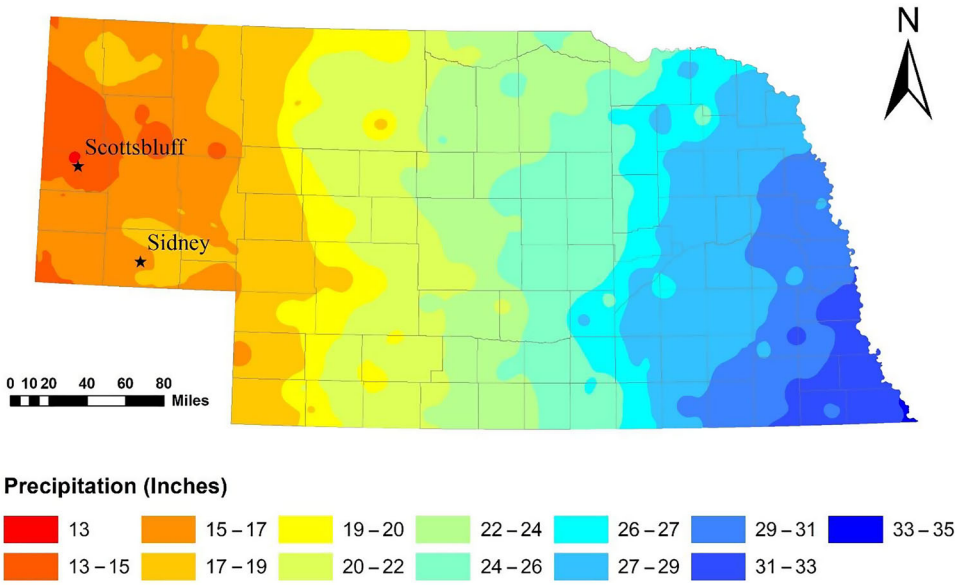


FIGURE 1 Study sites (black stars) within the Nebraska Panhandle. Colored regions represent the precipitation range across the state. Precipitation data from 1993 to 2023 were obtained from http://climod.unl.edu/.

We hypothesized that cereal grasses or their mixtures (if not all, at least some) would accumulate greater biomass with improved forage nutritive value compared to other species, due to their better adaptability to semiarid environment. The objective of this study was to evaluate the biomass and nutritive value of grasses, legumes, and brassicas, grown alone or in mixtures, under semiarid conditions. By assessing metrics such as establishment, biomass, carbon-to-nitrogen (C:N) ratios, forage nutritive value, and organic C and N contents, this research expands on existing knowledge while providing critical data for producers in this underrepresented region.

2 | MATERIALS AND METHODS

2.1 | Study sites and soil description

Experimental plots were established at the University of Nebraska-Lincoln High Plains Agricultural Laboratory near Sidney, NE (41°07′03″ N, 102°58′09″ W; elevation: 1297 m), and the Panhandle Research, Extension, and Education Center at Scottsbluff, NE (41°53′32″ N, 103°40′48″ W; elevation 1198 m). Both sites have a semiarid climate, with a mean 30-year annual precipitation of 404 mm at Sidney and 394 mm at Scottsbluff (Figure 1). The mean annual temperature at both sites is approximately 9°C. The soil at the Sidney site was characterized as Keith silt loam (fine-silty, mixed, superactive, mesic Aridic Argiustoll), and the Scottsbluff site as Tripp very fine sandy loam (coarse-silty, mixed, superactive, mesic Aridic Haplustolls). The mean monthly temperature and total monthly precipitation during the growing period (March to May) in 2022 and 2023, along with their respective 30-year average at both sites, are presented in Figure 2. Weather data were obtained from the High Plains Regional Climate Center CLIMOD database at http://climod.unl.edu/.

2.2 | Experimental design and treatments

At each site, the experimental design was a randomized complete block with four replications. Each individual plot was 1.52 m wide by 9.14 m long. A total of 20 species were tested (Table 1).

Seeding rates were intentionally set higher than standard recommendations to ensure robust establishment and uniform growth, thereby facilitating reliable comparisons among species. CCs were planted on March 4, 2022 and April 3, 2023 at Sidney and on March 23, 2022 and March 7, 2023 at Scottsbluff using a 1.52 m wide drilling control system research drill (Great Plains 3P600). The planting delay at Sidney in 2023 was caused by excessive soil moisture conditions, which prevented timely field operations. Legumes were inoculated with NOC010—Micro Noc: Multi Spectrum (Sono Ag, LLC)—no more than 24 h prior to drilling. CCs were preceded by sunflowers (*Helianthus annus* L.) in 2022 and by wheat (*Triticum aestivum* L.) in 2023 at Sidney, and by corn in both years at Scottsbluff. At both sites, experimental plots were maintained under no-tillage and rainfed conditions. Glyphosate (N-phosphonomethyl glycine 53.8%) was applied at a rate of 0.38 L ha^{-1} 2 weeks before planting each year for weed control (UNL, 2025). This lower-than-standard rate was selected to minimize chemical input and reduce potential herbicide carryover while still achieving adequate weed suppression. CCs were grown for 60–81 days (i.e., terminated on May 25,

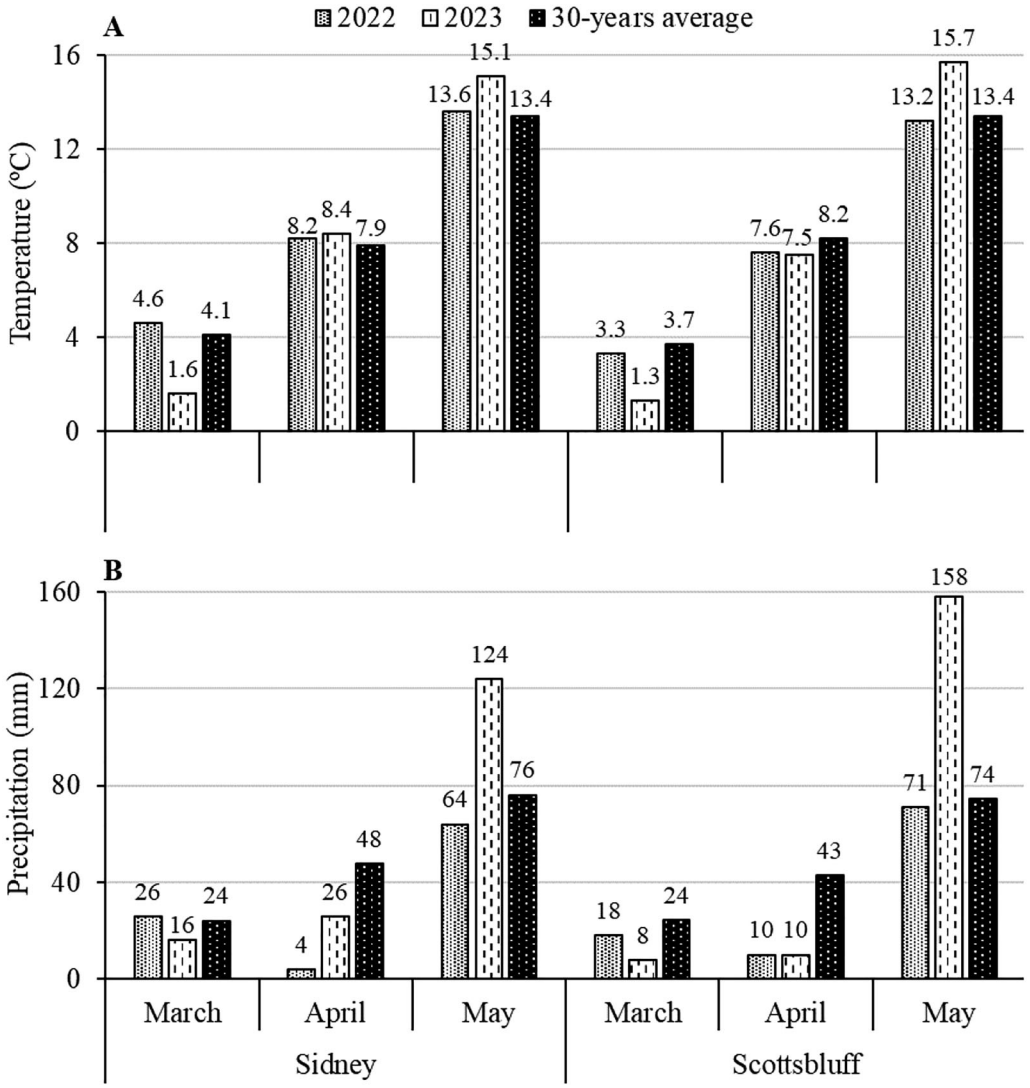


FIGURE 2 Mean monthly temperature (A) and total monthly precipitation (B) during the cover crop growing period in 2022 and 2023, along with their respective 30-year average at Sidney and Scottsbluff, NE.

2022 and June 1, 2023 at Sidney, and on May 24, 2022 and May 22, 2023 at Scottsbluff). Termination timing was determined based on the schedule that allowed for planting main summer cash crops such as dry beans (*Phaseolus vulgaris* L.), corn, peas (*Pisum sativum* L.), and sugar beets (*Beta vulgaris* L.) in the rotation.

2.3 | Weather during the CC growing period (March to May)

In 2022, Sidney experienced a slightly warmer temperature than the 30-year long-term average (Figure 2A). The average temperature was 8.8˚C in 2022 and 8.4˚C in 2023, compared to the 30-year average of 8.5˚C. Notably, the average temperature surpassed the long-term average by 0.5˚C, 0.3˚C, and 0.2˚C in March, April, and May of 2022, and by 0.5˚C and 1.7˚C in April and May of 2023. The total precipitation was 94 mm in 2022 and 166 mm in 2023, compared to the 30-year average of 148 mm (Figure 2B). This represented a 37% decrease in precipitation in 2022 but a 12% increase in 2023 compared to the long-term average. Notably, precipitation in May 2023 spiked, recording 63% greater than the corresponding long-term average.

At Scottsbluff, both 2022 and 2023 experienced slightly cooler temperatures compared to the long-term average (Figure 2A). The average temperature was 8.0˚C in 2022 and 8.2˚C in 2023, in contrast to the 30-year average of 8.4˚C. Specifically, temperatures were lower by 0.4˚C, 0.6˚C, and 0.2˚C in March, April, and May of 2022, and by 2.4˚C and 0.7˚C in March and April of 2023. However, there was a notable increase of 2.3˚C in average temperature in May 2023. The precipitation pattern at Scottsbluff mirrored that of Sidney (Figure 2B). The total precipitation was 99 mm in 2022

TABLE 1 Plant type, species, variety, and seeding rates of spring-planted cover crops used at Sidney and Scottsbluff, NE, in 2022 and 2023.

Plant type	Species	Variety	Seeding rate (kg ha^{-1})
Grasses			
1	Barley	Lavina	112
2	Barley	Robust	112
3	Barley	P919	112
4	Oat	Goliath	112
5	Oat	Hayden	112
6	Oat	Jerry	112
7	Triticale	Surge	112
Legumes			
8	Pea	4010	78
9	Pea	Survivor	78
10	Pea	WyoWinter	78
11	Faba bean	Petite	78
Brassicas			
12	Rapeseed	Bonar	9
13	Rapeseed	Barsica	9
14	Collard	Impact	9
Two-way mixtures			
15	Oat + pea	Goliath + 4010	Each species is half of its sole seeding rates
16	Oat + pea	Hayden + 4010	Each species is half of its sole seeding rates
17	Triticale + pea	Surge + 4010	Each species is half of its sole seeding rates
Three-way mixtures			
18	Barley + pea + rapeseed	Lavina + 4010 + Barsica	Each species is one-third of its sole seeding rates
19	Oat + pea + rapeseed	Goliath + 4010 + Barsica	Each species is one-third of its sole seeding rates
20	Triticale + pea + rapeseed	Surge + 4010 + Barsica	Each species is one-third of its sole seeding rates

and 176 mm in 2023, compared to the 30-year average of 141 mm. This represented a 30% decrease in precipitation in 2022 but a 25% increase in 2023 compared to the long-term average. Particularly, precipitation in May 2023 surged, recording a substantial 114% greater than the corresponding long-term average.

2.4 | Data collection

Stand count, plant height, and ground cover proportion were measured 4–5 weeks after planting to evaluate the establishment of CCs. Stand count for each species was determined by recording the total number of live upright plants with an erect main stem (no tillers) excluding weeds within a 0.19 m^2 quadrant from random spots within each plot. For sole species, plant height (measured with a ruler from the ground level or from the collar to the arch of the highest fully expanded leaf) was recorded. Plant height for mixtures was not measured. Ground cover (%) in the field was estimated using the CANOPEO mobile app (version 2.0), developed by Oklahoma State University. This app calculates green area based on color ratios of red to green (R/G) and blue to green (B/G) and an excess green index (2G-R-B) (Patrignani & Ochsner, 2015).

To estimate biomass at termination, when CCs were at the mid-vegetative stage, fresh samples were hand-clipped from a 0.19 m^2 quadrat placed at a randomly selected spot within each plot, avoiding plot edges and visually atypical areas. Biomass was determined by oven drying the samples at 65°C for 72 h. Biomass was ground to pass through a 0.5-mm screen and sent to a commercial laboratory (Ward Laboratories Inc. to determine C and N concentrations via the dry combustion method with a LECO C:N analyzer (LECO Corporation). Total C and N contents were calculated by multiplying C or N concentrations by the biomass. The forage nutritive value was assessed using near-infrared reflectance spectroscopy (NIRS) with a FOSS DS2500 NIR spectrometer (FOSS Analytical) and WinISI software. Calibrations were sourced from the NIRS Forage and Feed Testing Consortium (NIRSC) using the grass hay equation released in 2022 and 2023, which was deemed appropriate for our samples. This calibration

TABLE 2 Calibration performance statistics for the grass hay equations used in 2022 and 2023.

Constituent	Year	Mean	SEC	R^2	SECV
Crude protein	2022	12.65	0.91	0.98	0.96
	2023	12.10	0.90	0.97	0.94
Acid detergent fiber	2022	38.34	1.69	0.95	1.80
	2023	38.29	1.76	0.94	1.83
Neutral detergent fiber	2022	58.91	2.40	0.96	2.50
	2023	58.87	2.38	0.96	2.48
Calcium	2022	0.48	0.10	0.75	0.11
	2023	0.48	0.10	0.75	0.11
Phosphorus	2022	0.21	0.04	0.79	0.04
	2023	0.21	0.04	0.79	0.04
Potassium	2022	1.72	0.33	0.83	0.35
	2023	1.72	0.33	0.83	0.35
Magnesium	2022	0.26	0.05	0.87	0.05
	2023	0.26	0.05	0.87	0.05

Abbreviations: R^2, coefficient of determination for calibration; SEC, standard error of calibration; SECV, standard error of cross-validation.

was used to estimate crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), total digestible nutrients (TDN), calcium (Ca), phosphorus (P), potassium (K), and magnesium (Mg). Calibration performance statistics for each constituent are summarized in Table 2. We acknowledge that the accuracy of NIRS predictions is closely tied to the quality and relevance of the calibration set. As emphasized by Castillo et al. (2025), validation against laboratory-measured results using independent samples outside the calibration dataset is essential when reporting forage nutritive values. Only grass species were selected due to their consistent ability to accumulate considerable biomass, positioning them as a potential forage source. Mixtures were not included because grasses dominated the biomass in mixtures (by over 70%), which would likely result in effects similar to those of sole grasses. Fresh subsamples were sent to a commercial laboratory (Ward Laboratories Inc.) immediately after sampling.

Biomass is influenced by growing degree days (GDDs) as they determine the length of the growing period and associated climatic conditions (Teasdale et al., 2004). Therefore, GDD was calculated using the formula:

$$\mathrm{GDD} = \left[(T\max + T\min)/2\right] - T_b,$$

where Tmax and Tmin represent maximum and minimum temperatures, and T_b is the minimum temperature at which growth ceases (base temperature) (Cao & Moss, 1989). A literature search suggested a T_b of 0°C for barley, oat, and triticale (Delatorre et al., 2021; Gallagher, 1979; Royo & Blanco, 1999), 4.1°C for pea (Raveneau et al., 2011), 1°C for faba bean (*Vicia faba* L.) (Kasim & Dennett, 1986), 3°C for rapeseed (*Brassica napus* L.) (Marshall & Squire, 1996), and 4.4°C for collard (*Brassica oleracea* L.) (Dufault et al., 1989). Moreover, a T_b of 0°C was assumed for two- and three-way mixtures containing either one barley, oat, triticale, pea, or rapeseed, as the error caused by this assumption is minimal (Baraibar et al., 2020). If the calculated GDD led to negative, it was recorded as zero, as GDD should always be positive (Elnesr & Alazba, 2016). Species sharing the same T_b had identical GDD (Table 3). GDDs were accumulated from planting to biomass sampling.

TABLE 3 Growing degree day accumulation for spring-planted cover crops from planting to biomass sampling.

	Growing degree days	
Species	Sidney (°C)	Scottsbluff (°C)
2022		
Barley	708	575
Oat	708	575
Triticale	708	575
Pea	419	343
Faba bean	636	515
Rapeseed	493	400
Collard	401	329
Two-way mixtures	708	575
Three-way mixtures	708	575
2023		
Barley	695	590
Oat	695	590
Triticale	695	590
Pea	466	361
Faba bean	637	531
Rapeseed	525	417
Collard	451	348
Two-way mixtures	695	590
Three-way mixtures	695	590

Note: Base temperature (T_b) was 0°C for barley, oat, and triticale, 4.1°C for pea, 1°C for faba bean, 3°C for rapeseed, 4.4°C for collard, and 0°C for two- and three-way mixtures.

2.5 | Statistical analysis

Biomass, C:N ratio, and forage nutritive value data were analyzed using the MIXED procedure with restricted maximum likelihood estimation to test the significance of species differences. Species were also grouped into broader categories based on plant type (functional traits) or mixture composition: grasses (e.g., barley, oat, triticale), legumes (e.g., pea, faba bean), brassicas (e.g., rapeseed, collard), two-way mixtures (e.g., Goliath + 4010, Hayden + 4010, Surge + 4010), and three-way mixtures (e.g., Lavina + 4010 + Barsica, Goliath + 4010 + Barsica, Surge + 4010 + Barsica). These categories were manually assigned in the dataset. To account for

environmental variability and improve the generalizability of results, year was treated as a random effect, with replications nested within each location–year combination as an additional random term. This structure allowed for generalization across years without making inferences about specific year and better captured variability associated with seasonal and site-level conditions. Fixed effects included species or plant type, location, and their interaction (species or plant type × location). When fixed effects were significant at $p = 0.05$, least square means and pairwise comparisons were performed using the PDIFF option. The SLICE option was used to interpret significant species or plant type × location interactions by comparing species or plant types within each location, and by comparing locations within each species or plant type. When the interaction effect was significant, main effects were not reported. Letter groupings for mean separation were generated using the PDMIX800 macro. Residual normality was assessed using the Shapiro–Wilk test. A second-degree polynomial regression was performed across sites to predict biomass as a function of total precipitation, average temperature, and GDD during the growing period using the PROC REG procedure. All statistical analyses were conducted using SAS software version 9.4 (SAS Institute Inc.).

3 | RESULTS

3.1 | Biomass of spring-planted CCs

Biomass ranged from 0.04 to 1.13 Mg ha^{-1} and was influenced by species, location, and their interaction (Table 4). At Sidney, Jerry oat had the greatest biomass (1.13 Mg ha^{-1}), exceeding other species by more than 60%. Lavina barley (0.71 Mg ha^{-1}), Robust barley, and the two-way mixture of Hayden oat + 4010 pea (both 0.67 Mg ha^{-1}) followed without differing from one another. Biomass averaged 0.67 Mg ha^{-1} for grasses (range: 0.47–1.13 Mg ha^{-1}), 0.30 Mg ha^{-1} for legumes (range: 0.16–0.53 Mg ha^{-1}), 0.09 Mg ha^{-1} for brassicas (range: 0.05–0.12 Mg ha^{-1}), 0.60 Mg ha^{-1} for the two-way mixtures (range: 0.52–0.67 Mg ha^{-1}), and 0.45 Mg ha^{-1} for the three-way mixtures (range: 0.38–0.59 Mg ha^{-1}).

At Scottsbluff, P919 barley (0.71 Mg ha^{-1}) and the three-way mixture of Lavina barley + 4010 pea + Barsica rapeseed (0.70 Mg ha^{-1}) had the greatest biomass. Other species with greater biomass included Lavina barley (0.64 Mg ha^{-1}), Robust barley (0.63 Mg ha^{-1}), Jerry oat (0.58 Mg ha^{-1}), and the two-way mixture of Hayden oat + 4010 pea (0.47 Mg ha^{-1}), all of which did not differ. Biomass averaged 0.52 Mg ha^{-1} for grasses (range: 0.33–0.71 Mg ha^{-1}), 0.20 Mg ha^{-1} for legumes (range: 0.08–0.29 Mg ha^{-1}), 0.08 Mg ha^{-1} for brassicas (range: 0.04–0.11 Mg ha^{-1}), 0.40 Mg ha^{-1} for the two-way mixtures (range: 0.36–0.47 Mg ha^{-1}), and 0.46 Mg ha^{-1} for the three-way mixtures (range: 0.31–0.70 Mg ha^{-1}). At both locations, Impact collard, Bonar and Barsica rapeseed, Petite faba bean, and Wyowinter pea had the lesser biomass (<0.20 Mg ha^{-1}). Biomass did not differ between Sidney and Scottsbluff for any species except Jerry oat, which had approximately twice the biomass at Sidney compared to Scottsbluff.

Biomass was also influenced by total precipitation, average temperature, and GDD during the growing period (Table 5). Across both locations, GDD explained the largest proportion of variance in biomass (44%), followed by average temperature (43%) and total precipitation (34%).

3.2 | Biomass, carbon-to-nitrogen (C:N) ratios, and organic C and N contents by plant type (functional traits)

There was no plant type × location interaction for biomass, organic C, or organic N; however, all three variables were affected by plant type (Table 6). On average, across locations, grasses had the greatest biomass (0.60 Mg ha^{-1}), similar to the two-way mixtures (0.50 Mg ha^{-1}), but greater than that of the three-way mixtures (0.46 Mg ha^{-1}), legumes (0.25 Mg ha^{-1}), and brassicas (0.09 Mg ha^{-1}). The three-way mixtures had greater biomass than legumes and brassicas, but it did not differ from the two-way mixtures. Organic C content followed a similar pattern. Grasses had the greatest C content (245 kg ha^{-1}), similar to the two-way mixtures (213 kg ha^{-1}), but greater than that of the three-way mixtures (192 kg ha^{-1}), legumes (107 kg ha^{-1}), and brassicas (33 kg ha^{-1}). The three-way mixtures had greater organic C content than legumes and brassicas but were not different from the two-way mixtures. For organic N, grasses again had the greatest content (21 kg ha^{-1}). The two-way and three-way mixtures did not differ, but both had greater N content than legumes and brassicas. Organic N content was also influenced by location, where Sidney had 55% greater organic N content than Scottsbluff across all plant types.

In contrast, the C:N ratio was affected by plant type, location, and their interaction (Table 6; Figure 3). At Sidney, the two-way mixtures (11.4) and grasses (11.3) had the greatest C:N ratios than the other plant types. Legumes (10.5) and the three-way mixtures (10.4) did not differ. At Scottsbluff, C:N ratios were 16%–47% greater across all plant types compared to Sidney. The two-way mixtures had the greatest C:N ratio (15.1), followed by the three-way mixtures (13.7). At both locations, brassicas had the lowest C:N ratios. Overall, C:N ratios ranged from 8.5 to 15.1.

3.3 | Forage nutritive value of spring-planted CCs

There were no species × location interactions for CP, ADF, NDF, TDN, Ca, P, or K concentrations (Table 7). However,

TABLE 4 Biomass of spring-planted cover crops at Sidney and Scottsbluff, NE, in 2022 and 2023.

Plant type	Species	Variety	Sidney (Mg ha^{-1})	Scottsbluff (Mg ha^{-1})
Grasses				
	Barley	Lavina	0.71bA	0.64abA
		Robust	0.67bA	0.63abcA
		P919	0.47bcdA	0.71aA
	Oats	Goliath	0.56bcdA	0.33defghA
		Hayden	0.64bcA	0.38bcdefgA
		Jerry	1.13aA	0.58abcdB
	Triticale	Surge	0.53bcdA	0.41bcdefA
Legumes				
	Pea	4010	0.53bcdA	0.25efghA
		Survivor	0.31deA	0.29efghA
		WyoWinter	0.19eA	0.17fghA
	Faba	Petite	0.16eA	0.08ghA
Brassicas				
	Rapeseed	Bonar	0.11eA	0.04hA
		Barsica	0.12eA	0.11fghA
	Collard	Impact	0.05eA	0.10fghA
Two-way mixtures				
		Goliath + 4010	0.52bcdA	0.37bcdefghA
		Hayden + 4010	0.67bA	0.47abcdeA
		Surge + 4010	0.62bcA	0.36cdefghA
Three-way mixtures				
		Lavina + 4010 + Barsica	0.59bcdA	0.70aA
		Goliath + 4010 + Barsica	0.38cdeA	0.31defghA
		Surge + 4010 + Barsica	0.38cdeA	0.39bcdefA
Source of variation				
Species (S)	***			
Location (L)	**			
S × L	*			

Note: Brassicas failed to establish in 2022 at both locations; therefore, only 2023 biomass data are presented. Means followed by same lowercase letters in a column are not significantly different among species within each location, and by same uppercase letters in a row are not significantly different between locations within each species at $p < 0.05$.

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

species and location influenced most variables, except for Ca (not affected by species) and NDF (not affected by location). Across locations, the barley varieties (Lavina, Robust, and P919) had the greatest CP concentration (225–227 g kg^{-1}), similar to those of the Goliath and Hayden oat (both 208 g kg^{-1}), but greater than Surge triticale (201 g kg^{-1}) and Jerry oat (189 g kg^{-1}). Surge triticale did not differ from Jerry oat. Surge triticale had the greatest ADF concentration (268 g kg^{-1}), comparable to Lavina and Robust barley (263–264 g kg^{-1}), but greater than the oat varieties (Goliath, Hayden, and Jerry: 229–252 g kg^{-1}) and P919 barley (248 g kg^{-1}). Goliath and Jerry oat did not differ. For NDF, Surge triticale (447 g kg^{-1}) and Robust barley (442 g kg^{-1}) had the greatest concentrations, exceeding oat varieties (389–410 g kg^{-1}) and P919 barley (416 g kg^{-1}), while it did not differ from Lavina barley (435 g kg^{-1}). Goliath oat again did not differ from Jerry oat. In contrast, Jerry oat had the greatest TDN concentration (765 g kg^{-1}), similar to Goliath oat (753 g kg^{-1}), but greater than the remaining species (720–742 g kg^{-1}). Surge triticale, Lavina, and Robust barley did not differ. Calcium concentrations ranged from 4.2 to 5.0 g kg^{-1} across species. Lavina barley had the greatest P concentration (4.6 g kg^{-1}), similar to Robust and P919 barley and Surge triticale (all 4.5 g kg^{-1}), but greater than the oat varieties. While Goliath and Hayden oat both had P concentrations of 4.4 g kg^{-1}, Jerry oat had the least (3.9 g kg^{-1}). Potassium concentrations were 7%–14% greater in all other species compared to Robust barley (33.7 g kg^{-1}) and Jerry oat (32.6 g kg^{-1}). Across species, the average

TABLE 5 Regression analysis showing the relationship between cover crop biomass and total precipitation, average temperature, and growing degree days (GDDs) during the growing period across two sites in Nebraska Panhandle.

Parameter	Equation	R^2	*n*	Significance
Total precipitation	Biomass = −3E − 06 × precipitation^2 + 0.003 × precipitation + 0.19	0.34	74	*
Average temperature	Biomass = 0.041 × temperature^2 − 0.744 × temperature + 3.75	0.43	74	***
GDD	Biomass = 6E − 07 × GDD^2 + 0.0004 × GDD − 0.01	0.44	74	***

Note: R^2 = coefficient of determination; *n* = number of data points or observations.
*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

TABLE 6 Biomass, carbon-to-nitrogen (C:N) ratio, and organic C and N contents of spring-planted cover crops at Sidney and Scottsbluff, NE, in 2022 and 2023.

Plant type	Biomass (Mg ha^{-1})	C:N ratio	Organic C (kg ha^{-1})	Organic N (kg ha^{-1})
Grasses	0.60a	12.2b	245a	21a
Legumes	0.25c	11.7b	107c	10c
Brassicas	0.09d	10.5c	33d	4d
Two-way mixtures	0.50ab	13.2a	213ab	17b
Three-way mixtures	0.46b	12.0b	192b	16b
Location				
Sidney	0.42a	10.4b	176a	17a
Scottsbluff	0.33a	13.5a	140a	11b
Source of variation				
Type (T)	***	***	***	***
Location (L)	NS	***	NS	*
T × L	NS	**	NS	NS

Note: Brassicas failed to establish in 2022 at both locations; therefore, only 2023 data are presented. Means followed by same lowercase letters in a column are not significantly different at $p < 0.05$.
Abbreviation: NS, not significant.
*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

TABLE 7 Forage nutritive value of spring-planted grass cover crops at Sidney and Scottsbluff, NE, in 2022 and 2023.

Species	Variety	CP (g kg^{-1})	ADF (g kg^{-1})	NDF (g kg^{-1})	TDN (g kg^{-1})	Ca (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Mg (g kg^{-1})
Barley	Lavina	225a[†]	263ab	435ab	725cd	4.9a	4.6a	37.1a	3.0a
	Robust	227a	264ab	442a	725cd	5.0a	4.5ab	33.7b	3.2a
	P919	225a	248bc	416bc	742bc	4.8a	4.5ab	36.6a	3.0a
Oats	Goliath	208ab	239cd	389e	753ab	4.6a	4.4b	35.9a	2.6b
	Hayden	208ab	252bc	410cd	738bc	4.6a	4.4b	37.0a	2.5b
	Jerry	189c	229d	391de	765a	4.2a	3.9c	32.6b	2.4b
Triticale	Surge	201bc	268a	447a	720d	4.7a	4.5ab	36.1a	2.4b
Location									
Sidney		229a	261a	417a	728b	5.4a	4.7a	36.7a	3.0a
Scottsbluff		195b	243b	420a	749a	3.9b	4.1b	34.4b	2.5b
Source of variation									
Species (S)		***	***	***	***	NS	***	***	***
Location (L)		**	**	NS	**	**	**	*	*
S × L		NS	NS	NS	NS	NS	NS	NS	*

Note: Means followed by same lowercase letters in a column are not significantly different at $p < 0.05$.
Abbreviations: ADF, acid detergent fiber; Ca, calcium; CP, crude protein; Mg, magnesium; NDF, neutral detergent fiber; NS, not significant; K, potassium; P, phosphorus; TDN, total digestible nutrients.
*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

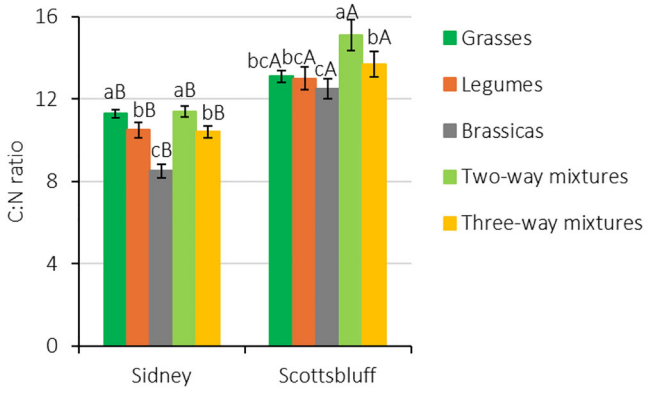


FIGURE 3 Interaction effect of cover crop plant type and location on carbon-to-nitrogen (C:N) ratio. Brassicas failed to establish in 2022 at both locations; therefore, only 2023 C:N ratio data are presented. Means (±standard error) with different lowercase letters are significantly different among plant types within each location, and with different uppercase letters are significantly different between locations within each plant type at $p < 0.05$.

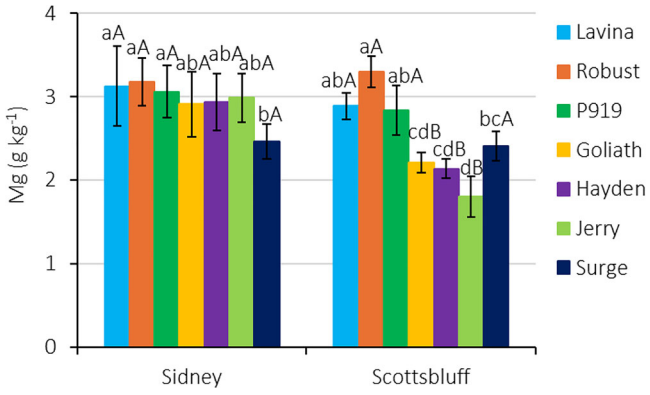


FIGURE 4 Interaction effect of cover crop species and location on magnesium (Mg). Means (±standard error) with different lowercase letters are significantly different among species within each location, and with different uppercase letters are significantly different between locations within each species at $p < 0.05$.

TDN concentration was 3% greater at Scottsbluff compared to Sidney. However, Sidney had greater concentrations of CP (by 18%), ADF (by 8%), Ca (by 40%), P (by 14%), and K (by 7%) than Scottsbluff.

In contrast to other mineral nutrients, Mg concentration was affected by species × location interaction (Table 7; Figure 4). At Sidney, barley varieties had the greatest Mg concentrations (3.1–3.2 g kg^{-1}) than Surge triticale (2.5 g kg^{-1}), with the oat varieties showing intermediate values (2.9–3.0 g kg^{-1}). At Scottsbluff, barley varieties again had greater Mg concentrations (2.8–3.3 g kg^{-1}) than the oat varieties (1.8–2.2 g kg^{-1}). Mg concentrations also differed between Sidney and Scottsbluff for oat varieties (Goliath, Hayden, and Jerry), with concentrations at Sidney being 32%, 37%, and 65% greater, respectively, than at Scottsbluff.

4 | DISCUSSION

4.1 | Environmental and site-specific effects on biomass

Biomass across sites and years was influenced by variation in growing duration and environmental conditions, particularly precipitation and temperature (Figure 2; Table 4). At Sidney, CCs grew for 81 days in 2022 and 60 days in 2023, receiving 78 and 151 mm of precipitation, respectively. In contrast, the growing period at Scottsbluff was shorter in 2022 (62 days) but longer in 2023 (76 days), with total precipitation of 48 and 156 mm, respectively. This variation influenced biomass accumulation, as evidenced by the regression analysis, where GDD explained 44% of the variation in biomass, followed closely by average temperature (43%) and precipitation (34%) (Table 5).

The impact of precipitation was particularly evident in 2022 when moisture deficits likely contributed to the failure of water-sensitive species such as rapeseed and collard. These species are known to be highly sensitive to drought during early growth stages (Batool et al., 2023; Ben Ammar et al., 2022). In contrast, the more favorable precipitation in 2023 likely supported improved establishment and growth. While GDD and temperature slightly surpassed precipitation as predictors of biomass, adequate early-season rainfall is critical for seed germination, root development, and vegetative growth (Whitmore & Whalley, 2009).

Despite the relatively shorter spring growing period (≤81 days), certain species like Jerry oat accumulated biomass above 1 Mg ha^{-1} (1.13 Mg ha^{-1} at Sidney), exceeding the threshold needed to reduce residual soil nitrate (Hively et al., 2009; Thapa et al., 2018). This biomass also contained approximately 476 kg ha^{-1} of organic C and 38 kg ha^{-1} of organic N. While modest, these values underscore the potential for spring-planted CCs to deliver ecosystem benefits even under environmental constraints, particularly when species are strategically selected.

4.2 | Drivers of species × location interaction

The species × location interaction for biomass can be attributed to differential species and mixture responses to site-specific environmental conditions, particularly precipitation timing, growing duration, and soil characteristics. For example, Jerry oat had nearly double the biomass at Sidney compared to Scottsbluff. This may be explained by more favorable March precipitation (26 mm) during critical early

growth stages and a longer 2022 growing period (81 days). Oat responds well to consistent early-season moisture, which promotes tillering and canopy development (Akey & Morrison, 1984). Moreover, the Keith silt loam soil at Sidney, with greater water-holding capacity, likely enhanced soil moisture retention, favoring oat growth under intermittent rainfall conditions.

In contrast, P919 barley had greater biomass at Scottsbluff (0.71 vs. 0.47 Mg ha^{-1} at Sidney), likely due to a higher total precipitation (156 mm), a longer 2023 growing period (76 days), and potentially more favorable soil microclimatic conditions. Barley's greater tolerance to low moisture and fertility (Jedel & Helm, 1991) may explain its relatively better performance in the Tripp very fine sandy loam soil at Scottsbluff.

Differences in mixture biomass also contributed to the observed interaction. At Sidney, two-way mixtures had greater biomass than three-way mixtures (0.60 vs. 0.45 Mg ha^{-1}), likely due to reduced interspecific competition and more efficient resource use during the shorter 2023 growing period (60 days). Under time- or moisture-limited conditions, simpler mixtures may better partition resources such as water and nutrients (Tilman et al., 1997). Conversely, at Scottsbluff, three-way mixtures had greater biomass compared to two-way mixtures (0.46 vs. 0.40 Mg ha^{-1}), possibly due to functional complementarity (e.g., variation in rooting depth, canopy structure, or N-fixing ability), which allowed more effective resource utilization in the coarser-textured soils (Blesh, 2018; Mueller et al., 2013). These site-specific responses highlight how even modest differences in precipitation timing, growing period, and soil texture can influence biomass outcomes.

4.3 | Influence of plant type on biomass and residue quality (C:N ratio)

Beyond environmental and site-specific influences, plant functional type also influenced both biomass and residue quality. Variability among grasses, legumes, and brassicas reflects their distinct physiological and biochemical characteristics. Although all evaluated species followed the C3 photosynthetic pathway, and legumes benefit from biological N fixation, grasses consistently had greater biomass than legumes and brassicas (Table 6). This may be attributed to the rapid early growth of grasses, their extensive fibrous root systems that enhance water and nutrient uptake, and their greater tolerance to drought and low soil fertility (Blum, 2014; Peratoner et al., 2016; Wang et al., 2021).

However, biomass across all plant types was relatively low (<1 Mg ha^{-1}), largely due to shorter growing durations and suboptimal weather during the study period. Delayed planting (April 3, 2023, at Sidney; March 23, 2022, at Scottsbluff) and relatively early termination (May 24–June 1) limited the growth period to 60–81 days. This was shorter than in previous studies at Sidney, where oat had biomass of 2.28 ± 0.23 Mg ha^{-1} (Calderón et al., 2016)–2.56 Mg ha^{-1} (Nielsen et al., 2015) under earlier planting (early March) and later termination (mid-June). Moreover, lower precipitation in 2022 further suppressed biomass accumulation. These results suggest that, when feasible, extending the spring growth period, by planting in early March and terminating in mid-June without interfering with summer cash crops, could increase biomass to amounts comparable with prior findings.

While grasses are valued for their greater biomass, the inclusion of at least one grass species with a legume in two-way mixtures resulted in biomass and organic C contents comparable to grasses alone (Table 6). This highlights the added value of functional diversity in balancing biomass with residue quality. The ability of these mixtures to match grasses in biomass while improving residue characteristics (C:N = 15.1) suggests a greater potential to moderate decomposition rates. These outcomes emphasize how blending complementary species can harness the strengths of individual functional traits, supporting multifunctionality in cropping systems (Finney & Kaye, 2017).

In contrast, legumes and brassicas had less biomass than grasses and mixtures, with brassicas being the least (Table 6). Brassicas also consistently had the lowest C:N ratios (Figure 3), likely due to their naturally greater N concentrations and lower proportions of structural C compounds such as cellulose and lignin (Housseinpour et al., 2010). At Scottsbluff, C:N ratios were greater across all plant types compared to Sidney, likely reflecting the 16 additional growing days in 2023, which allowed further accumulation of C-rich structural tissues. This aligns with the understanding that C:N ratios increase with plant maturity (Rai et al., 2020; Tsai & Chang, 2022).

Despite these species and site differences, all plant types had C:N ratios below 16, likely due to termination at the mid-vegetative stage when tissue N concentrations are still high due to active growth and metabolic demand (Hou et al., 2021). As a result, residues from all species are likely to decompose rapidly, accelerating N mineralization and supporting early-season N supply for subsequent crops (B. Ghimire et al., 2017; Hou et al., 2021). These findings highlight the utility of spring-planted CCs for enhancing nutrient cycling potential even under constrained growing periods.

4.4 | Forage nutritive value and biomass trade-offs in spring-planted CCs

This study revealed clear species differences in forage nutritive value among small grain CCs. Notably, barley and oat had greater CP and TDN concentrations (Table 7), highlighting their potential as high-nutritive forage sources. These species

had CP concentrations exceeding 200 g kg^{-1}, a concentration associated with improved forage nutritive value (Acharya et al., 2023; Deen et al., 2019). However, these greater nutritive values did not correspond with greater biomass (>1 Mg ha^{-1}, except for Jerry oat), illustrating a trade-off between forage mass and nutritive value. Species that accumulated more biomass tended to have greater amounts of structural carbohydrates, which increased low-solubility fiber concentrations (Botero-Londoño et al., 2021; Welti et al., 2020).

Termination at the mid-vegetative stage also influenced forage nutritive value. Early termination typically results in greater CP concentrations due to a greater proportion of N-rich cell contents in immature plant tissue (Johnson et al., 2001). This trend was supported by our results: grasses terminated before physiologically matured stage had not only greater CP concentrations but also the greatest organic N content (Tables 6 and 7), underscoring the importance of timely termination to optimize forage nutritive value.

Beyond protein and energy content, mineral concentrations, particularly Ca, P, K, and Mg, are essential for meeting livestock nutritional requirements. Among the evaluated species, Jerry oat had lower mineral concentrations, suggesting that mineral supplementation may be necessary when it is used as a sole forage source.

Site-specific differences in forage nutritive value were also observed. Samples from Sidney had greater concentrations of CP, ADF, Ca, P, and K compared to those from Scottsbluff (Table 7). These differences likely reflect the 13% greater total precipitation at Sidney, which may have enhanced soil water availability, nutrient diffusion, and microbial activity that promotes nutrient mineralization (Bauke et al., 2022; Ochoa-Hueso et al., 2020). Increased precipitation supports nutrients uptake through improved mass flow and diffusion processes (Marschner, 2012).

While several species had high forage nutritive value, biomass across plant types was modest (<1 Mg ha^{-1}), suggesting limited potential for forage harvest. Instead, these species may be better suited for brief, opportunistic early-season grazing or for filling temporary forage gaps, especially during spring shortages. Compared to conventional forage crops commonly grown in the region, such as alfalfa (*Medicago sativa* L.), bromegrass (*Bromus spp.*), crested wheatgrass (*Agropyron cristatum* L.), and millet (*Panicum miliaceum* L.), barley and oat were comparable or even superior in CP concentrations (Guretzky et al., 2021; Pflueger, 2019; Weichenthal et al., 2008). However, their limited biomass and greater ADF concentrations suggest that they are better suited as supplemental rather than primary forage sources. Therefore, producers considering spring CCs primarily for forage should carefully assess whether site-specific biomass amounts are sufficient to meet their needs.

5 | CONCLUSIONS

This study underscores the influence of environmental factors, particularly GDD and precipitation, in driving biomass accumulation in semiarid regions. Grasses consistently exceeded legumes and brassicas in biomass under variable environmental conditions, indicating their strong adaptability and resilience to semiarid climate constraints. In contrast, brassicas failed to establish during drier conditions, emphasizing the importance of careful species selection based on local moisture availability and temperature patterns. Grass–legume mixtures were promising in balancing biomass and nutrient cycling functions, combining the greater biomass potential of grasses with the lower C:N ratios of legumes. All evaluated species had C:N ratios below the thresholds that support early-season nutrient release, highlighting their potential contributions to nutrient cycling in cropping systems.

Although spring-planted CCs had only moderate biomass, the greater forage nutritive value of selected small grain species offers opportunities for short-term or opportunistic grazing. In systems where early forage availability is critical, these species may help bridge spring feed gaps while delivering additional ecosystem benefits. Overall, spring CC planting could be an alternative in semiarid regions, helping avoid winterkill risks and autumn planting constraints. With moderate biomass, high nutritive value, and the potential to contribute to soil C and N, spring-planted CCs can offer both economic and ecological advantages. While biomass harvest may not always be justified, these CCs can serve as valuable components of multifunctional systems by enhancing nutrient cycling, seasonal forage availability, and soil health in semiarid environments.

AUTHOR CONTRIBUTIONS

Vesh R. Thapa: Data curation; formal analysis; investigation; software; visualization; writing—original draft. **Katja Koehler-Cole**: Conceptualization; methodology; supervision; writing—review and editing. **Amanda Easterly**: Methodology; supervision; writing—review and editing. **Nicolas Cafaro La Menza**: Supervision; writing—review and editing. **Grace E. Pacheco**: Data curation; investigation; visualization; writing—review and editing. **Bridget McKinley**: Data curation; investigation; visualization; writing—review and editing. **Andrea Basche**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available at https://doi.org/10.5061/dryad.x0k6djhwn.

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