

University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

Department of Agronomy and Horticulture:
Dissertations, Theses, and Student Research

Agronomy and Horticulture, Department of

5-3-2024

Using Annual Forages to Replace Declining Cool-Season Grass Pasture Availability

Jonathon Matthew Jenkins
University of Nebraska-Lincoln

Follow this and additional works at: <https://digitalcommons.unl.edu/agronhortdiss>



Part of the [Agricultural Science Commons](#), [Agronomy and Crop Sciences Commons](#), [Botany Commons](#), [Other Animal Sciences Commons](#), [Other Plant Sciences Commons](#), and the [Plant Biology Commons](#)

Jenkins, Jonathon Matthew, "Using Annual Forages to Replace Declining Cool-Season Grass Pasture Availability" (2024). *Department of Agronomy and Horticulture: Dissertations, Theses, and Student Research*. 260.

<https://digitalcommons.unl.edu/agronhortdiss/260>

This Thesis is brought to you for free and open access by the Agronomy and Horticulture, Department of at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Department of Agronomy and Horticulture: Dissertations, Theses, and Student Research by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

USING ANNUAL FORAGES TO REPLACE DECLINING COOL-SEASON GRASS

PASTURE AVAILABILITY

by

Jonathon Matthew Jenkins

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Agronomy

Under the Supervision of Professor John Guretzky

Lincoln, Nebraska

May, 2024

USING ANNUAL FORAGES TO REPLACE DECLINING COOL-SEASON GRASS
PASTURE AVAILABILITY

Jonathon Matthew Jenkins, M.S.

University of Nebraska, 2024

Advisor: John Andrew Guretzky

As land area in grain crop production increases in the US Midwest, perennial pasture availability decreases but the demand increases. Matching the seasonal growth patterns of C₃ and C₄ plant species to grow forages that are complementary allows producers to fill production gaps in otherwise monoculture systems and possibly increase overall productivity. One way to fill the forage production gap of C₃ grass dominated pastures is by producing a warm-season, annual forage in a separate field. However, with continual reductions in land availability, this may not be an option. Using two studies, our objectives were to improve forage crop production within existing perennial pastures and in historical cropland converted to annual pastures. We also wanted to compare the effects of N fertilized grass monocultures to non-N fertilized grasses mixed with legumes to see if N fertilization could be replaced by legumes. To improve the total forage production within smooth brome grass pastures, we sod-seeded sorghum × sudangrass but found too large a reduction in smooth brome grass forage mass the following year with no improvement in forage production. To sustainably improve forage production and distribution within land area under annual forage production, we tested the viability of a double cropped forage system using fall planted triticale cut once in the spring followed by pearl millet cut once in the summer and compared it to a perennial system containing smooth brome grass. We found that timely precipitation was crucial to the success of the

annual system and when abundant, the double cropped annual forage system produced most of the forage during the summer. This contrasts with smooth brome grass pastures, which produced the greatest during the spring. Nitrogen fertilization and mixed grass-legume produced similar forage mass in smooth brome grass pastures, but mixed grass-legume pastures produced less mass in the annual forage system.

Table of Contents

<i>Table of Contents</i>	<i>1</i>
<i>List of Figures</i>	<i>4</i>
<i>List of Tables</i>	<i>6</i>
CHAPTER 1 - REVIEW OF LITERATURE	13
Abstract.....	13
Why Do Forage Production Gaps Exist?	13
Using Summer Annuals to Fill the Summer Slump	19
Using Cool Season Annuals to Fill Gaps in Spring and Fall	25
Opportunities to Fill Multiple Gaps Within a Pasture	30
N Fertilization vs Legume mixes.....	37
Conclusion.....	39
Literature cited.....	41
CHAPTER 2 - HERBAGE ACCUMULATION AND NUTRITIVE VALUE OF A DOUBLE-CROPPED ANNUAL FORAGE SYSTEM AND A DIVERSE PERENNIAL CIRCULAR FORAGE SYSTEM	60
Abstract.....	60
Introduction	61
Materials and Methods	64
Site History.....	64
Experimental Design.....	66
Vegetation Data Collection	67
Animal Management.....	68
Plant Litter.....	69
Forage Nutritive Value.....	70

Statistical Analysis.....	70
Results	71
Weather Conditions.....	71
Discussion	86
Double Crop Annual Forage System	86
Diverse Perennial Circular Forage System	90
System Comparison	92
Conclusion.....	95
Literature cited.....	96

***CHAPTER 3 - HERBAGE MASS RESPONSES TO SOD SUPPRESSION WITH
GLYPHOSATE IN PASTURES INTERSEEDED WITH SORGHUM X***

<i>SUDANGRASS</i>	<i>104</i>
Abstract.....	105
Introduction	106
Materials and Methods	108
Site History.....	108
Experimental Design.....	109
Stocking Cycles, Interseeding, and Sod Suppression	110
Herbage Mass Components.....	111
Statistical Analysis.....	112
Results	112
Weather Conditions.....	112
Analysis of Variance	113
Pasture Type Effects	113
Sod Suppression After Interseeding Effects	114
Treatment Year Effects	117
Discussion.....	117
Conclusions	122
Literature Cited.....	123

FIGURES..... 131

TABLES 141

List of Figures

- Figure 1. Treatment and data collection timeline for the Double Cropped Annual Forage System and the Diverse Perennial Circular Forage System..... 131
- Figure 2. Average monthly precipitation of the study years from August 2021 to September 2023 and their 30-year averages at Ithaca, Nebraska. 132
- Figure 3. Average monthly temperatures of the study years from August 2021 to September 2023 at Ithaca, Nebraska. 133
- Figure 4. Bare ground and litter cover averaged across N fertilized grass and mixed grass-legume pastures expressed as percentages of basal cover in the double cropped annual forage system (DCAFS) in 2022 (a) and 2023 (b). 134
- Figure 5. Bare ground and litter cover averaged across N fertilized grass and mixed grass-legume pastures expressed as percentages of basal cover in the diverse perennial circular forage system (DPCFS) in 2022 (a) and 2023 (b). 135
- Figure 6. Experimental layout at the University of Nebraska – Lincoln Eastern Nebraska Research and Extension Center at Mead, NE, from 2020-2022. The experiment had a split-plot design with six, 1.20-ha main plots (1-6) and six, 6.70 m² subplots (orange rectangles, not to scale). The main plots consisted of mixed-legume smooth brome grass (*Bromus inermis* Leyss.) pastures and N-fertilized smooth brome grass pastures. The subplots consisted of sod suppression after sorghum × sudangrass interseeding treatments. The subplot treatments were established within one randomly selected paddock (A-F) within each main plot in 2020 and in an adjacent paddock in 2021. The six, 0.20 ha paddocks were used for rotational stocking of 3-4 crossbred steers (*Bos taurus* L.) to maintain even utilization and vegetation heights within and across main plots throughout the study duration. 136
- Figure 7. Monthly precipitation during the study years and longer-term average from 1981-2010 at Mead, Nebraska. 137
- Figure 8. Perennial grass mass in summer as affected by glyphosate rate after interseeding pastures with sorghum × sudangrass at Mead, NE. The summer sampling took place 8 weeks after treatment. Two rotational stocking cycles with cattle grazing preceded the sorghum × sudangrass interseeding and glyphosate

applications in spring each year. Each mean \pm SE represents two pasture types and three replicates (n = 6). 138

Figure 9. Sorghum \times sudangrass, weedy grass, and total herbage mass in summer as affected by glyphosate rate after interseeding sorghum \times sudangrass into pastures at Mead, NE. The summer sampling time took place 8 weeks after interseeding and sod suppression treatments. Two rotational stocking cycles preceded sorghum \times sudangrass interseeding and the glyphosate treatment applications each year. Each mean \pm SE represents two pasture types, two years, and three replicates (n = 12). 139

Figure 10. Perennial grass and total herbage mass in the next spring as affected by glyphosate rate after interseeding sorghum \times sudangrass the previous spring in pastures at Mead, NE. The next spring sampling time took place 50 weeks after interseeding and sod suppression treatments. Heavy grazing by cattle in two rotational stocking cycles preceded sorghum \times sudangrass interseeding and the glyphosate treatment applications the previous spring. 140

List of Tables

Table 1. ANOVA of herbage mass components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions at a double cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.	141
Table 2. ANOVA of herbage mass components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions at a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.	141
Table 3. ANOVA of N concentrations in herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions at a double-cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.	142
Table 4. ANOVA of N concentrations in herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions in a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.	142
Table 5. ANOVA of N yields of herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions at a double-cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.	143
Table 6. ANOVA of N yields of herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y),	

and their interactions at a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.	143
Table 7. ANOVA of NDF concentrations in herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions in a double-cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.	144
Table 8. ANOVA of NDF concentrations in herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions in a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.	144
Table 9. ANOVA of IVOMD concentrations in herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions in a double-cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.	145
Table 10. ANOVA of IVOMD concentrations in herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions in a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.	145
Table 11. ANOVA of IVOMD yields of herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions at a double-cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.	146
Table 12. ANOVA of IVOMD yields of herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year	

(Y), and their interactions in a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.	146
Table 13. ANOVA of bare ground and litter count data as affected by pasture type (P), time (T), year (Y), and their interactions in a double-cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.	147
Table 14. ANOVA of bare ground and litter count data as affected by pasture type (P), time (T), year (Y), and their interactions in a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.	147
Table 15. ANOVA of steer initial body weights, final body weights, average daily body weight gains, and total body weight gains as affected by pasture type (P), year (Y), and their interactions in a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.	147
Table 16. Forage grass, legume, forage species, and total herbage mass in the double-cropped annual forage system (DCAFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean.	148
Table 17. Weedy grass and weedy species mass at the double-cropped annual forage system grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer). Weedy grasses included barnyardgrass, yellow foxtail, giant foxtail, and crabgrass and weedy species included weedy grasses and other forbs including prostrate knotweed, mares tail, and velvetleaf.	149
Table 18. Weedy grass and weedy species mass at the double-cropped annual forage system grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer). Weedy grasses included barnyardgrass, yellow foxtail, giant foxtail, and crabgrass and weedy	

species included weedy grasses and other forbs including prostrate knotweed, mares tail, and velvetleaf.	149
Table 19. Forage grass, forage species, weedy grass, weedy species, and total herbage mass in the diverse perennial circular forage system (DPCFS) grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth bromegrass and the legumes birdsfoot trefoil, alfalfa, and red clover. Weedy grass species was dominated by yellow foxtail and weedy species consisted of weedy grasses and the weedy forbs wild mustard, field bindweed, and horsenettle.....	150
Table 20. Forage grass, legume, forage species, and total herbage N concentrations in the double-cropped annual forage system (DCAFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types; at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean; and in the sampling years 2022 and 2023. Weedy species included barnyardgrass, yellow foxtail, giant foxtail, crabgrass, prostrate knotweed, mares tail, and velvetleaf.	151
Table 21. Forage grass, legume, forage species, weedy species, and total herbage N yields in the double-cropped annual forage system (DCAFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean. Weedy species included barnyardgrass, yellow foxtail, giant foxtail, crabgrass, prostrate knotweed, mares tail, and velvetleaf.	152
Table 22. Forage grass, forage species, and total herbage N concentrations in the diverse perennial circular forage system (DPCFS) grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth bromegrass and the legumes birdsfoot trefoil, alfalfa, and red clover.	153

- Table 23. Forage grass, legume, and forage species N concentrations in the diverse perennial circular forage system (DPCFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover. 153
- Table 24. Forage grass, forage species, weedy species, and total herbage N yields in the diverse perennial circular forage system (DPCFS) grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover. Weedy species consisted of yellow foxtail, wild mustard, field bindweed, and horsenettle. 154
- Table 25. Forage grass, forage species, and total herbage N yields in the diverse perennial circular forage system (DPCFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover. 154
- Table 26. Forage grass, forage species, weedy species, and total herbage NDF concentrations in the double-cropped annual forage system (DCAFS) grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean. Weedy species included barnyardgrass, yellow foxtail, giant foxtail, crabgrass, prostrate knotweed, mares tail, and velvetleaf. 155
- Table 27. Forage grass, legume, forage species, weedy species, and total herbage NDF concentrations in the double-cropped annual forage system (DCAFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage

grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean. Weedy species included barnyardgrass, yellow foxtail, giant foxtail, crabgrass, prostrate knotweed, mares tail, and velvetleaf.	156
Table 28. Forage grass, forage species, weedy species, and total herbage NDF concentrations in the diverse perennial circular forage system (DPCFS) grazing enclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover. Weedy species consisted of yellow foxtail, wild mustard, field bindweed, and horsenettle.	157
Table 29. Forage grass, forage species, weedy species, and total herbage NDF concentrations in the diverse perennial circular forage system (DPCFS) grazing enclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover. Weedy species consisted of yellow foxtail, wild mustard, field bindweed, and horsenettle.	158
Table 30. Forage grass, legume, forage species, weedy species, and total herbage IVOMD concentrations in the double-cropped annual forage system (DCAFS) grazing enclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean. Weedy species included barnyardgrass, yellow foxtail, giant foxtail, crabgrass, prostrate knotweed, mares tail, and velvetleaf.	159
Table 31. Forage grass, legume, forage species, weedy species, and total herbage IVOMD yields in the double-cropped annual forage system (DCAFS) grazing enclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture	

types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean. Weedy species included barnyardgrass, yellow foxtail, giant foxtail, crabgrass, prostrate knotweed, mares tail, and velvetleaf.	160
Table 32. Forage grass, forage species, weedy species, and total herbage IVOMD concentrations in the diverse perennial circular forage system (DPCFS) grazing enclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover. Weedy species consisted of yellow foxtail, wild mustard, field bindweed, and horsenettle.	161
Table 33. Forage grass, forage species, weedy species, and total herbage IVOMD yields in the diverse perennial circular forage system (DPCFS) grazing enclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover. Weedy species consisted of yellow foxtail, wild mustard, field bindweed, and horsenettle.	162
Table 34. ANOVA of herbage mass components including forage species: perennial grasses, legumes, sorghum × sudangrass, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (T), sod suppression (S) after interseeding, sampling date (D) after sod suppression, sod suppression after interseeding year (Y), and their interactions at Mead, Nebraska from 2020-2022.....	163
Table 35. Perennial grass, total forage species, and total herbage mass in pastures at Mead, NE relative to sampling date after interseeding × interseeding year interactions. The summer sampling took place 8 weeks after interseeding and application of sod suppression treatments while the next spring sampling date took place 50 weeks after interseeding and sod suppression.	164

CHAPTER 1 - REVIEW OF LITERATURE

Abstract

Perennial forage systems are the backbone of ruminant livestock production because they are productive and nutritious, they are relatively inexpensive to maintain by nature, and they provide several benefits to the ecosystem. Forage systems in the midwestern United States are dominated by cool season perennial species, but these create a gap in forage production during the early spring, late fall and winter, and especially the summer. One way to produce forage during these gaps is to establish annual forages, which can be manipulated by planting time and management to balance the production from perennial forages. This review identifies established and novel management strategies to use annual forages during these production gaps to fill livestock nutrient requirements.

Why Do Forage Production Gaps Exist?

In the midwestern United States, pasture systems are often dominated by cool season grass species such as smooth brome grass (*Bromus inermis* Leyss.), tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.), Kentucky bluegrass (*Poa pratensis* L.), reed canarygrass (*Phalaris arundinacea* L.) and orchardgrass (*Dactylis glomerata* L.) which all contain C3 photosynthesis. The C3 photosynthetic pathway exhibits highest photosynthetic rates during cool temperatures, with photosynthesis occurring between 0 and 30° C and rapidly declining around 35° C (Moser and Hoveland, 1996; Sage and Kubien, 2007). At high temperatures, C3 plants have reduced C fixation rates because of a process called photorespiration, whereas the enzyme (Rubisco) which normally fixes CO₂ to a 5-carbon sugar (RuBP), fixes O₂ to it instead (Ogren, 1984).

Instead of creating energetic sugars for the plant to derive ATP and reducing power from, photorespiration consumes ATP and NADPH and thus is a waste of solar and chemical energy (Peterhansel et al., 2010). Oxygenation is increased under certain conditions such as hot and dry environments because Rubisco's affinity for O₂ increases with temperature (Ku and Edwards, 1977a), CO₂ solubility is reduced in the aqueous cytoplasm and stroma (Ku and Edwards, 1977b), and stomatal gas exchange is reduced in an effort to conserve water (Cornic and Briantais, 1991). For these reasons C3 plants tend to be less productive during summers in the midwestern region of the U.S. This is commonly referred to as the "summer slump" (Denison and Perry, 1990; Ottman and Mostafa, 2014).

Even though this review grouped cool season perennial grasses together under one category because of their growth characteristics, it is an incomplete description of them and should be recognized as such. Many of these grasses occupy different growth habits and niches which might affect yield distribution into the spring and fall. For example, 'Justus' orchardgrass and smooth brome grass are able to maintain yields under 80% tree shade compared to being grown under full sun in Missouri. In fact, smooth brome grass yields were higher when grown under 50% shade compared to the full sun treatment (Lin et al., 1998). Another niche of smooth brome grass is that it dominates the western portion of the Midwest because of its superior ability to resist and survive dry conditions relative to other cool season species (Sheaffer et al., 1992b). Inversely, reed canarygrass has an excellent ability to thrive in high moisture riparian areas within pastures (Jensen et al., 2018) and Kentucky bluegrass is good at taking over bare patches in degraded rangelands and under other warm and cool-season pasture grasses (Grant et al., 2020).

Differing from C3 photosynthesis, the C4 photosynthetic pathway provides an evolutionary advantage by blocking photorespiratory processes. In this pathway, CO₂ comes into the plant via stomata and instead of being directly fixed to RuBP, it is fixed to phosphoenolpyruvate (PEP) to become a 4-carbon acid which is shuttled to specialized bundle sheath cells through intercellular pores called plasmodesmata; here, the CO₂ is released and concentrated around rubisco molecules (Ehleringer and Monson, 1993). This process makes photorespiration nil in C4 type plants because it prevents O₂ from coming in contact with rubisco. In addition to decreased photorespiration, C4 plants have high photosynthetic rates under warmer temperatures compared to C3 plants. Depending on the species, warm season grasses can continue to photosynthesize in temperatures from 7° to 45° C and have higher optimum temperatures than C3 (Sage and Kubien, 2007). A study conducted on numerous types of C3 and C4 plants showed that under high light intensity and temperatures above 30°C, C4 plants exhibited higher quantum yields than C3 plants, that is, a higher efficiency of photon absorption (Ehleringer and Björkman, 1977). At these conditions, they attribute the superior quantum yield by C4 plants to a threshold temperature when C3 photorespiratory losses exceed the additional ATP requirement from 4-carbon acid shuttling of C4 photosynthesis.

A secondary advantage to C4 photosynthesis is enhanced water use efficiency. In all terrestrial plants, there are pores on the epidermis of their leaves called stomata. Stomata are largely responsible for atmospheric exchange of H₂O and CO₂ which are important for evapotranspiration and carbon assimilation, respectively (Lawson and Matthews, 2020). Overall, both C3 and C4 species tend to exhibit increases in daytime stomatal aperture from environmental cues like high quality light, elevated CO₂, good

leaf water status, and high nutrient availability (Farquhar and Sharkey, 1982). Since C4 plants concentrate CO₂ at the site of rubisco, they exhibit lower stomatal conductance than C3 plants which results in higher water retention, especially during unfavorable conditions (Collatz et al., 1992). Another reason C4 plants have higher water use efficiency compared to C3 plants is due to their rapid stomatal closure and reduced 'leakiness' (Ozeki et al., 2022). However, these advantages aren't without some costs. It has been implied by (Way et al., 2014) that C4 plants experience a higher photosynthate cost during times of water loss than C3 plants but have similar or greater net carbon assimilation. This means that although C4 plants have higher WUE, they may suffer more severely under specifically droughty conditions (Ghannoum, 2009).

The advantages of the C4 photosynthetic pathway extend beyond enhancements to carbon assimilation and transpirational water loss, such as the augment in multiple types of nitrogen use efficiency (NUE) calculations. Foremost, C4 plants have a higher NUE in terms of biomass production per unit of assimilated N which is likely the result of a reduced requirement of Rubisco (Brown, 1978) inherently decreasing the leaf N content compared to C3 plants (Oaks, 1994). Another way C4 plants they have higher N use efficiency is by partitioning less N towards photosynthetic enzymes. For example, lambsquarter (*Chenopodium album*, C3) invests 10-27% of its assimilated N into rubisco while redroot pigweed (*Amaranthus retroflexus*, C4) only invests 5-9% plus an additional 2-5% in PEPcarboxylase. At similar leaf N per unit area, lambsquarter had 1.5 to 2.6 times more CO₂ saturated rubisco than redroot pigweed but a slower photosynthetic rate (Sage et al., 1987). In part by these advantages, C4 species are able to produce more

above and belowground biomass than C3 species in soils containing low available N (Brown, 1985).

Physiological differences between photosynthetic mechanisms provide both advantages to the plant and to animals who graze them. As was previously described, the high quantities of leaf rubisco in C3 plants inherently yield higher crude protein (CP) concentrations than their C4 counterparts. Crude protein determination is a method of estimating protein in ruminant feeds for the purpose of forming a diet ration (von Keyserlingk et al., 1996). Based on a standardized calculation of %N x 6.25, CP can be expressed as a percent of total feed, or for further N fractionation used to estimate protein digestibility (Licitra et al., 1996).

Fiber is another component of forage quality relevant to photosynthetic types that can be better understood by looking into anatomical differences between their cellular and tissue characteristics. One distinction includes that C4 plants tend to have thicker, waxier, and more lignified cell wall on the outer epidermal layer of leaves and stems which is impermeable and requires mechanical degradation to complete digestion (Wilson, 1993). This effect was visualized when green panic (*Panicum maximum*) and Italian ryegrass (*Lolium multiflorum*) were artificially chewed and digested in vivo. Results showed that relatively large pieces of epidermis of green panic remained attached to undigested bundle sheath cells and took over 48 hours to complete digestion because of the epidermis's lowly penetrable barrier. The epidermis of Italian ryegrass was fully separated within 24 hours, though, and neither type had significant digestion of longitudinal fibers (Wilson et al., 1989). Because of the prominent epidermis in C4 plants, rumination is likely to be a more impactful component to forage digestion

compared to C3 plants, assuming other differences affecting fiber digestibility, like maturity, are equal.

Other less digestible features of C4 type plants include bundle sheath cells due to their secondary cell wall thickening by lignification. Since bundle sheath cells are primarily found in the leaves of C4 plants, they particularly affect leaf blade digestibility. A study conducted on multiple species found bundle sheath cell digestibility to be about 50% for 20 hours in vitro (Akin et al., 1983). A different study showed that only 25-50% of bundle sheath cells in mature indiangrass (*Sorghastrum nutans*) and big bluestem (*Andropogon gerardii*) leaf blades were degraded following a 128 hour in vivo incubation period (Hastert et al., 1983). Referring back to the photosynthetic pathways of C4 plants provides a deeper look into why indigestible bundle sheath cell walls are more problematic than the fiber component alone. When CO₂ is fixed inside plant cells (mesophyll for C3 and bundle sheath for C4), the sugars produced can be used to form starch granules within the chloroplasts (Raines, 2003). Since C4 plants store these starch in their bundle sheath cells, a large proportion of the digestible component is physically protected from the rumen microbes. On average, leaf blades have about 25% more indigestible epidermis and bundle sheath cells and because of this, have about 22% less easily digestible tissue like mesophyll and phloem cells in vitro (Akin and Burdick, 1975).

Consider the differences between photosynthetic types and the role seasonal temperature distribution plays on them. In perennial native warm season forage systems, most of the growth occurs between June and September and forage production gaps exist in spring and fall months during the growing season. In forage systems that largely

consist of cool season species, the summer slump is obvious during July through September and growth moderately increases through the fall as plants prepare for winter. For the purposes of this review, the depression in Autumnal forage production below that of spring production is considered to be a gap that needs to be filled to meet nutrient requirements of ruminant livestock.

In general, it's a sound economic practice to try to fill these production gaps with grazable forage rather than with concentrates or stored forage supplementation by reducing livestock production and maintenance costs. For example, when annual forages are productive and of good nutritive value, grazing annual forages is less expensive in growing cattle (McCartney et al., 2004; Kumar et al., 2012), developing heifers (Funston and Larson, 2011), and cow-calf pairs (Willms et al., 1993; Anderson et al., 2014) compared to supplementation with stored feedstuffs.

Using Summer Annuals to Fill the Summer Slump

Perennial warm season forages can be a vital component of forage systems in the midwestern U.S. by having the ability to fill the gap of the summer slump (Keyser et al., 2022), although they represent a dwindling proportion of pastureland in the midwestern US mainly due to overgrazing. For example, big bluestem pastures subjected to repeated defoliation with recovery periods of <40 d resulted in especially traumatic responses to the plant, including a reduction in root mass and a large reduction in tiller regrowth (Mousel et al., 2005). Warm season perennial species are also notorious for difficult establishment procedures and often require multiple years before they are available to graze. In addition, warm season annual forages like sorghum x sudangrass have similar average forage yields to perennials like switchgrass, but are more dependent upon

summer moisture for production (Gelley et al., 2016). However, many warm season perennials require lots of management and upfront costs through high seed costs, stratification or chilling periods, seedbed preparation, and weed management with herbicides (Bragg and Sutherland, 1989; Kindiger, 1993; Mitchell and Britton, 2000). In the short term, it may be more profitable to utilize annual warm season forages to produce forage during the summer slump but in the long term, production costs will decrease as seeding costs of perennials are amortized across years. However, the importance of annuals in the long term may be more valuable to a producer by filling unforeseen gaps, and reducing risk associated with yearly weather patterns that affect the growth of perennial forages.

There are a variety of summer annuals used to produce forage during the summer slump. Some of the most common warm season grasses include many sorghum species (*Sorghum* spp.), pearl millet (*Pennisetum americanum*), crabgrass (*Digitaria sanguinalis*), teff (*Eragrostis tef*), and corn (*Zea mays*). Some common heat tolerant annual forage species are legumes including cowpea (*Vigna unguiculata*), forage soybean (*Glycine max*), and sunn hemp (*Crotalaria juncea*) while some other forbs include sunflower (*Helianthus annuus*) and buckwheat (*Fagopyrum esculentum*). Each of these annual forage types have certain applications to fit the goals of the producer. For example, if they wish to produce the most biomass in mechanically harvested systems, monocultures of warm season grass species fertilized with N may be the best option. If they wish to have the highest crude protein and the lowest fiber concentrations, it is generally thought that it is advantageous to include more legumes as part of the seed mixture (Ibrahim et al., 2012). However, legumes are prone to low forage yields and consequently no

improvement to the nutritive value of the system in combination with the grass (Contreras-Govea et al., 2013). A more important factor than plant selection for maintaining nutritive value is the defoliation strategy, which also affects subsequent forage yield by changing where new growth originates from (Creel and Fribourg, 1981)

Grasses tend to have the greatest contribution to dry matter production and nutrient yields for ruminant livestock in warm season annual forage systems, so species and cultivar selection are still crucial to the success of the system. Cultivars of sorghums used for forage production can be broken down into 3 main categories: true forage sorghum (*Sorghum bicolor*), sudangrass (*Sorghum halepense* var. *sudanese*), and sorghum x sudangrass hybrids. In a grazing study, true forage sorghum cultivars were found to have the largest stem diameter and the least amount of tillering. Because of this, they tend to have a lower leaf to stem ratio and are likely the better option for ensiling than the other types. Sudangrass is on the other side of the spectrum and had the greatest tissue consumption and was better utilized for grazing in sheep and cattle, probably because it has smaller stems and many tillers, and has a relatively high proportion of leaf to stem by weight. On one hand this characteristic of sudangrass leads to a high potential for lodging if harvest is delayed, but it also results in high palatability (Rabas et al., 1970). Sorghum x sudangrass cultivars also tend to have more tillers and smaller stems than forage sorghum (Venuto and Kindiger, 2008). Under single cut systems, sorghum x sudangrass hybrids generally have similar or higher yields than their parent forage sorghum cultivar, and both have greater yield potential than the sudangrass parent (Glamoclija et al., 2011). A study done on 300 forage sorghum cultivars and 137 sorghum-sudangrass cultivars showed that one cut forage sorghum varieties surpass

sorghum-sudangrass cultivars for total digestible nutrients (TDN) and ultimately have higher predicted milk yield across April and July (Pupo et al., 2022). Under grazing systems, however, sudangrass tends to have similar or greater fat corrected milk yields compared to sorghum x sudangrass (Cunningham and Ragland, 1971). Despite differences among sorghum type and cultivar selection, they all remain viable options for increasing summer forage yield in a cool season dominated forage system.

One important benefit to sorghum and pearl millet cultivars is their superior water use efficiency compared to corn. Traditionally used as a grain crop, pearl millet has grown in popularity as a summer annual forage crop since breeding in the mid 1900s began producing dwarf, trichomeless, and increased leaf to stem ratio varieties which increased forage quality and animal performance (Andrews and Kumar, 1992). Sorghum, corn, and pearl millet grown for forage under a gradient of irrigation regimes showed that all three produced similar single cut forage yield under adequate water supply, but DM yields of corn rapidly declined with decreasing water supply whereas sorghum and pearl millet maintained higher yields under moderate and severe drought stress. In this study, the sorghum variety was able to maintain forage production under moderate drought stress better than pearl millet, but both became similar under severe drought stress (Singh and Singh, 1995). A similar effect was also seen by Bhattarai et al. (2020b) when they had one year with better distribution of rain during vegetative growth than the other, and saw that single cut corn and sorghum outproduced pearl millet during the well distributed year. However, sorghum was statistically similar and had a tendency towards greater yields to pearl millet during the less distributed year. Both sorghum and pearl millet had higher yields than corn silage fertilized at 50-60 kg N ha⁻¹ (Bhattarai et al., 2020b). From

the research that has been conducted in dry growing conditions, silage type sorghum cultivars seem to be better than corn and pearl millet on the basis of forage production and crop growth rate whereas corn tends to have the highest in vitro dry matter digestibility (IVDMD) and pearl millet accumulates the most crude protein of the three crops (Bhattarai et al., 2020a).

Perhaps a more important difference to account for among sorghum species compared to other summer annual forages goes beyond yield and digestibility components, but rather their difference in accumulation of antinutritional metabolites. Prussic acid (hydrogen cyanide) is a toxic gas formed during chewing of plant tissues containing cyanogenic glucosides where they mix with beta-glucosidases, a process called cyanogenesis (Jones, 2007). Sorghum species partition the glucoside, dhurrin, fairly equally between stems and leaves, but its levels are increased by multiple stressors including moisture deficit and frosting (Gleadow et al., 2016). Lauriault et al. (2021) observed 68 kg greater cattle BW gain ha⁻¹ on pearl millet than sorghum-sudangrass grazed in the fall due to pearl millet being prussic acid free in post-frost conditions and 2.2 additional Mg DM ha⁻¹ of sorghum-sudangrass were left ungrazed because of potential toxicity (Lauriault et al., 2021). Young tissues have significantly higher prussic acid concentrations than mature tissue, so it is well established that allowing forage sorghum to mature makes most cultivars safe for grazing (Haskins et al., 1987; Gleadow et al., 2016). It is also possible that increasing grazing selectivity decreases the risk for prussic acid poisoning as sheep and deer were seen to favor acyanogenic plants of the same species, though this study was observational (Cooper-Driver et al., 1977). Until further research addresses cyanogenic preference by livestock, the current best

management practice is to reduce selectivity by rotationally grazing sorghum species. Most extension publications warn that animals tend to prefer new growth first and suggest that sorghum species should not be grazed until 45-60 cm tall as a rule-of-thumb to be sure that tissues are mature enough to dilute prussic acid potential (Lehmkuhler, 2011; Strickland et al., 2009; Whittier & Stanton, 2011). Although sorghum species may be the most productive and drought tolerant types of warm season annual forages, they have a clear disadvantage compared to other warm season grasses.

Using warm season annual forages may become increasingly important with a changing climate, as the summer slump becomes more dramatic from increasing atmospheric temperatures and variability in precipitation. One study done to predict climate warming effects on grain and forage sorghum yields found that there was a 0.53 Mg ha⁻¹ increase in forage yield for every degree centigrade increase up to +4 degrees under typical moisture availability in Argentina (Druille et al., 2020). In another climate change scenario, where temperature and atmospheric CO₂ concentrations increase, and rainfall decreases, dryland annual ryegrass/forage sorghum double-crop are modeled to resist annual DM yield decline whereas both perennial ryegrass and tall fescue pastures were predicted to decrease in yield under these changes (Pembleton et al., 2020). In another paper by this author, where only elevated atmospheric CO₂ was modeled against crop parameters from baseline levels, we see that dryland wheat, oats, and annual ryegrass all increase in crop biomass more than dryland forage sorghum (Pembleton et al., 2016). This is likely why the cool season annual grasses do not experience a decrease in forage production during theoretical elevated temperature and reduced moisture projections, as springtime moisture and temperatures are already forgiving.

Using Cool Season Annuals to Fill Gaps in Spring and Fall

Despite differences between species mentioned previously, cool season grasses still experience some level of growth rate reduction during late fall, winter, and early spring in addition to the summer slump. It has long been understood that successful perennial cool-season grass species prioritize root growth as winter approaches. In North Dakota, Power (1988) measured top and bottom growth of smooth brome grass across the growing season and found that root mass increased the most between 9 September and 1 October which vastly exceeded the growth rate of aboveground biomass at that time (Power, 1988). It is because of this adaptation that benefits the overwintering survival of perennial cool season grasses that creates a gap in forage production during fall months, when the climate should be conducive to moderate or high cool-season forage production.

A tried and true method of producing fall forage is to establish a cool-season annual in late summer or early fall which doesn't have the capacity to overwinter and continues growing as long as environmental conditions allow. Some common examples of these include spring cereal grains like oats and barley; brassicas such as turnip, radish, swedes, and forage rape; and legumes including Austrian winter pea.

Research conducted in Wisconsin examining small grains for fall and spring forage found that spring grains (oats, barley, and spring triticale) planted in mid-august and cut once produced 1.1-1.6 tons DM ac-1 of forage yield during the fall while winter small grains (wheat, rye, and winter triticale) produced only 0.3-0.7 tons DM ac-1 and noted this was due to the winter small grains' preparation for winter dormancy. During spring, winter small grains had more than double the forage yield of spring grains' fall

growth but had only 9.5-10.1% CP and 84-105 relative feed value (RFV) while spring grains were 12.1-19.7% CP with 155-164 RFV. In simpler terms, winter small grains produced more quantity in the spring but spring small grains produced more quality forage in the fall. When one spring and one winter small grain were planted together, forage yields were reduced in both fall (compared to spring small grain monocultures) and spring (compared to winter small grain monocultures). In this study, forage nutritive value of the mix was as good or better during the spring than when winter grains were planted in monocultures (Maloney et al., 1999). In Nebraska, a four-year study grazing crossbred steers on oats planted after chopping corn silage and after high moisture corn harvest showed that oats planted after corn silage produce over twice the forage mass of oats planted after high moisture corn, ultimately yielding 111 kg ha⁻¹ and 65 kg ha⁻¹ gain, respectively (Brinton et al., 2019). This large difference was mainly due to the oats planted after high moisture corn having an average of 33% less GDD than the oats planted after corn silage, though harvest dates were not shown.

In the Midwest, oats remain a viable option to produce forage during the fall with relatively high nutritive values. However, adding a forage brassica to the mixture has the potential to further increase forage CP and digestibility. In Nebraska, turnips and radishes planted with oats were seen to increase and maintain CP and IVOMD in the main late fall and winter production gap from November through January. During the span of these three months, turnips had 22.8-24.9% CP, radishes had 25.6-27.9% CP, and oats had 15.8-17.9% CP. Although turnips had slightly less crude protein, they were similar in digestibility and both reduced slowly across time, starting with around 88% and reducing to between 81.8% and 83.5% IVOMD (Lenz et al., 2019).

A one-year study in Ohio on fall-born lambs (24 kg BW) strip grazing monocultures of oats and turnips sown in mid-August, and August stockpiled tall fescue, turnips provided the highest ADG at 107 g day⁻¹ whereas oat alone only produced 13 g day⁻¹ and stockpiled tall fescue produced 34 g day⁻¹. In this study, oats reduced in forage quality across the 57 day grazing period due to winter weather events. This emphasizes the benefit of including a brassica in fall and winter grazing as day 0 of grazing exhibited the following nutritive values: TDN in oats were similar to stockpiled pastures but were less than turnip, CP in oats were greater than both stockpile pasture and turnips, and similar forage yields were reported at turnout across all three pasture species (3404-3566 kg ha⁻¹) (Campbell et al., 2021). In central Nebraska, cross-bred steers grazing monoculture oats gained 1.95 lb day⁻¹ while steers grazing an oat/rapeseed mixture gained 2.11 lb day⁻¹, decreasing cost of gain by \$0.05/lb as the mixture had reduced seed costs (Riley et al., 2019). In Michigan, Red Angus steers (437 kg BW) in their last 70 days of finishing, grazing an oat/turnip mixture, gained 138.3 kg/ha but steers grazing stockpiled perennial grass-legume pastures only gained 99.9 kg ha⁻¹ (Maciel et al., 2022). In this study, oat/turnip pastures planted in early June had forage yields exceeding stockpiled pasture yields, but IVDMD of the annual mixture were lower than stockpiled pastures in two out of three years. In a typical system, there are very few opportunities to plant an oat/brassica mixture this early as wheat harvest typically occurs in late June or early July and corn silage harvest begins even later in the midwestern US.

In the southern US, annual ryegrass has been proven as a successful annual forage because of its ability to grow high quality forage during fall, winter, and early spring in monocultures (Redfearn et al., 2002) and planted with cereal rye (Islam et al., 2011;

Butler et al., 2012). A 5-year study in Oklahoma concluded that a producer could have similar net returns continuously grazing stocker cattle on a cereal rye/annual ryegrass mixture as they could a newly planted novel endophyte tall fescue variety, though annual ryegrass expenses were higher. This was because annual pastures produced an average of 491 kg ha⁻¹ gains while tall fescue pastures produced an average of 349 kg ha⁻¹ gains over the 5 years (Islam et al., 2011). Research conducted in central Missouri reveals annual ryegrass may have potential for winter stockpiling in more northern latitudes. When the moisture and temperature are close to average for this area, forage yields of 'Marshall' annual ryegrass can accumulate to above 2000 kg ha⁻¹ with 15% ADF and above 17% CP, but these qualities and forage yield deteriorate throughout cold winter temperatures. When moisture and temperatures are above average, Marshall annual ryegrass can accumulate forage over winter and reach close to 3500 kg ha⁻¹ by March and stay below 20% ADF and above 20% CP. In these conditions, cereal rye outyields annual ryegrass across each collection date, but decreases in quality in the spring much more rapidly after February (Kallenbach et al., 2003). When annual ryegrass and cereal rye were in a mixture, they were seen to produce 3000-4000 kg ha⁻¹ of high quality forage (30% ADF and 14-15% CP) by the beginning of May (Kallenbach et al., 2006).

Even though Maloney et al. (1999) reported moderate to low forage quality in accumulated winter small grains, they do have the opportunity to be a productive and nutritious forage during the early spring production gap before reaching maturity. Steers grazing cereal rye in Nebraska until late April produced gains of 1.4-1.5 kg d⁻¹ and returns were shown to be between \$62 and \$70 ac⁻¹ (Conway et al., 2019). Unpublished data in Nebraska spring grazing wheat, rye, and winter triticale suggest there is little

differentiation in profitability between species with an average cost per animal unit month (AUM) around \$24. From this study, Drewnoski et al. (2018) suggests winter cereal grains can, in fact, be cost effective early spring grazing options in the midwestern US that fit crop production systems (Drewnoski et al., 2018).

Distribution of DM yields and nutritive values among cereal grain types are thought to differ, which may affect the suitability of grazing systems. In Minnesota, Phillips et al (2021) investigated nutritive values of grazed wheat and cereal rye across time and found that while total tract neutral detergent fiber digestibility (TTNDFD) reduced at the same rate across species as they mature, wheat growth was linear and rye growth was cubic. Beginning grazing on 25 April at early elongation stage, forage yields were similar between wheat and rye but in just 4 days, rye began to accumulate forage at a faster rate for a few weeks until growth became similar to wheat, around the second week of May. Around the last week of May, they saw wheat forage yields exceed rye while becoming similar in CP, after wheat began with a higher CP than rye and they declined linearly with different slopes (Phillips et al., 2021). These data suggest that rye has the ability to capitalize on an earlier window of growth than wheat. In southern Oklahoma, a more comprehensive analysis between plant species mechanically harvested multiple times by comparing 30 wheat, 14 rye, and 12 winter triticale varieties agree as they saw rye and triticale tend towards the greatest growth, earlier in the season than wheat (Kim et al., 2017). In Georgia, rye yields have also historically been shown to produce more forage in late-winter than triticale and wheat (Bruckner and Raymer, 1990).

To date, there are relatively few grazing studies in the midwestern US that investigate cattle performance on winter cereals and the few that exist are contrasting in profitability. This is probably because the studies were designed to fit row cropped systems by terminating the forage crop prior to grain crop planting dates which maximize yields but don't optimize profitability of both. Partially for this reason, one Iowa study concluded that while spring grazing lactating cows on cereal rye until 1 May helped to diminish profit loss of planting a cereal rye cover crop, average net returns were still negative since grazable forage was low (Plastina et al., 2023). Economic research on grazed winter cereal grains double cropped with a grain harvested row crop should be done to evaluate how whole system profitability changes with varying termination time of the annual forage and subsequent grain crop planting date.

Opportunities to Fill Multiple Gaps Within a Pasture

Double cropped annual forages have the opportunity to fill forage gaps across multiple season, but forage production is highly dependent on termination time and planting practices between them. The most common example of this is to plant a winter cereal grain in the fall, graze or harvest in spring, terminate, and plant corn for silage. In these double crop systems, total forage yields are generally greater but can be less than monoculture corn silage systems if termination of the winter cereal is delayed too long (Krueger et al., 2012). Acharya et al. (2017) recommends that a cereal rye cover crop should be terminated >10 d to maximize corn yield, though debate is still ongoing. More recent literature claims that no-till corn grain yields planted following cereal rye will be less than those planted without a cover crop and may increase prevalence of plant diseases, reduced soil temperatures, and allelopathy from rye; all of which can reduce

corn yields (Plastina et al., 2023). In this study, cereal rye terminated between 17 days before planting and 6 days after planting resulted in similar corn yields, all a loss of less than or equal to 1 Mg ha⁻¹ (16 bu ac⁻¹). Rye contains three allelochemicals which are released into soils during residue breakdown after termination including 2-benzoxazolinine (BOA), 4-benzoxazine-3(4H)-one (DIBOA), and 2,4-dihydroxy-7-methoxy-(2H)-1,4-benzoxazine-3(4H)-one (DIMBOA). In no-till cotton fields in Texas, soil concentrations of DIBOA was reduced by grazing in December after the third consecutive year of rye but by February, DIBOA and DIMBOA were similar between grazed and ungrazed treatments. In August after May termination, grazed rye treatments had greater concentrations of DIMBOA in their soils (Li et al., 2013). However, more recent literature shows that the release of these chemicals occur within the first day or two and subsequent breakdown occurs within the first 10-20 days before the slope reduces to an asymptote (Rice et al., 2022). Therefore, no conclusions can be made about the grazing effect on allelochemicals in a relevant timeframe but it can be assumed that the reduction in corn yields planted in rye residues from Plastina et al. (2023) are probably because soil temperatures are cooler. Additionally, when tilled between forage crops including a cereal grain has also been shown to decrease corn silage yields, but increase total annual forage yields . One Pennsylvania study indicates that the tillage may have been unnecessary to maintain corn silage yields and increase total forage production (Fouli et al., 2012), though harvest dates were not reported so the evidence on whether this was from a gap between cereal grain termination and corn planting, or variability between these studies remains inconclusive.

An increasingly researched variation on double-cropped annual forage systems is to replace the corn for another warm season forage variety and harvest it throughout the summer. A seemingly obvious benefit to replacing the corn silage is the improvement in forage distribution during the summer slump and perhaps decreased livestock performance costs associated with yardage and feeding. In Iowa, a double-cropped system doing a single harvest of cereal rye and single harvest of sorghum produced more forage than a single harvest monoculture sorghum at high N rates while at moderate to low N rates, they were similar in 3 out of 4 years in Ames and 3 out of 5 years at Chariton (Buxton et al., 1999). This effectively distributed the forage across both spring and summer and increased CP in harvested pastures over a monoculture stand of sorghum. In Kansas, a winter triticale/forage sorghum double crop produced forage yields higher than or similar to a forage sorghum double crop cut at optimum stages (Holman et al., 2020). In both of these studies, ADF was similar to or higher in the winter cereal than sorghum. Indeed, these double-cropped systems provide an agronomic advantage into forage production and nutritive value, but additional research is imperative before making conclusions about animal performance in a grazed pasture as management has significant impacts on forage quality and seasonal distribution over mechanically harvested pastures.

Of the few studies, one Minnesota study rotationally grazing lambs (29-32 kg) on a double-cropped annual forage of sudangrass, cowpea, soybean, or kochia after a forage harvest of barley hay found that while soybean and cowpea produced the best individual animal performance (0.20 kg day⁻¹; 224 and 263 kg ha⁻¹, respectively), sudangrass and kochia resulted in the best gains on a land area basis (0.15 kg day⁻¹; 330 and 309 kg ha-

1). These pastures were split into two paddocks and grazed once through for approximately 14 d each; perhaps even better performance and more gains on these summer annuals could be achieved if regrowth had been grazed. (Sheaffer et al., 1992a). Clearly a productive and moderate quality warm season grass species like sudangrass has potential to perform in a grazed double-cropped annual forage program.

Stockpiled forage is accumulated forage for grazing at a later time (Allen et al., 2011). This can be done with either cool- or warm-season forages and be utilized during dormant seasons of production. For example, summer and fall stockpiling is a common practice in cool season perennial grasses common in the midwestern US (e.g. tall fescue, smooth brome grass) that can allow forage to be grazed in late fall, winter, and early spring before breaking dormancy and accumulation of new growth; all while maintaining their quality compared to other winter forage sources like corn residues (Hitz and Russell, 1998). Cool-season annuals also have potential to be stockpiled as mentioned in earlier sections, examples being oats, barley, forage brassicas, and annual ryegrass. Additionally, warm season annuals may be stockpiled and utilized during late fall and winter months to fill those production gaps in double cropped forage systems. For production systems that need higher nutritive value stockpile, late summer planting can provide accumulated growth that hasn't reached mature stages yet. In spring or early summer planted warm season annuals, midsummer grazing can be a management strategy that reduces maturity within a pasture, utilizes the forage while it's at nutritious stages, and subsequent rest in late summer can allow for stockpile to accumulate.

A 5-year study grazing pregnant, commercial beef cows with summer planted monoculture foxtail millet or a mix containing some level of spring cereals, legumes,

warm season annual grasses and forbs, and forage brassicas each year. In this North Dakota study, planting the summer forage was not as productive in a double-cropped system (planted after a spring planted oats or barley) as in a single-cropped system where the summer forage was planted earlier in the season. However, double-cropping foxtail millet or the cocktail mix in the summer after the spring cereal produced the lowest cost (\$0.68-\$1.76 hd-1 d-1) annual system compared to the single summer cropping systems (\$0.83-\$2.20) even though they produced the most forage (Sedivec et al., 2011). In a similar study, cows grazing a double-crop annual forage system containing spring barley followed by a stockpiled mix of oats, field pea, sorghum-sudangrass, sunflower, radish, and turnip in late October through late November gained 2.02 lb day⁻¹, maintained body condition, and had a lower maintenance cost (\$0.89 hd-1 d-1) than in a drylot system (\$2.13 hd-1 d-1) or in a system without the spring barley (\$1.92 hd-1 d-1) (Gaugler et al., 2014). Swath grazing stockpiled warm season annual forages may also be a potential method in midwestern forage systems but should be utilized relatively quickly or some degree of decline in nutritive value should be expected, depending on temperature and moisture exposure (Dahlke et al., 2022).

One less accepted management practice to fill multiple seasonal production gaps within a pasture using annuals is sod-seeding. As the name suggests, sod-seeding is a method of no-till drilling or interseeding of forage crops into living, established pastures (Koch et al., 1983). Some already well accepted practices to fill production gaps using sod-seeding include seeding perennial legumes into cool season (Sheaffer and Swanson, 1982; Kunelius et al., 1988) and warm season (Gettle et al., 1996) perennial grass pastures. While southern latitudes and coastal regions of the United States can

successfully grow cool season annual forages in bermudagrass and bahiagrass through fall and winter months (Swain et al., 1965; Hill et al., 1985), mostly only recent studies have begun to evaluate the effects of sod-seeding annual forages into perennial grasses in the Midwest. In north-central Georgia, one older study evaluating sorghum-sudangrass and rye were seen to improve forage yields when sod-seeded into tall fescue. In 25% chemically suppressed sods, rye improved winter forage yields by about 43% (1000 kg ha⁻¹) following sod-seeded sorghum-sudangrass which improved summer forage yields by 32% (1600 kg ha⁻¹); ultimately increasing total forage yields by 31% (2300 kg ha⁻¹) and filling forage gaps throughout the year (Belesky et al., 1981). In Iowa, sod-seeding forage sorghum or sweet sorghum with an additional 63 lb N ac⁻¹ has been shown to increase forage yields in new stands of alfalfa by an average of 1.8 tons ac⁻¹ (37%) and in new stands of reed canarygrass by an average of 1.1 tons ac⁻¹ (41%) while only slightly reducing nutritive values in these systems (Buxton et al., 1998). Within the reed canarygrass plots, both sorghum species were noted to have reduced vigor and appeared chlorotic, even at rates of 125 lb N ac⁻¹ and was hypothesized to be due to allelopathy. Research done in alfalfa found that reed canarygrass extracts have little effect on germination whereas tall fescue and smooth bromegrass did (Chung and Miller, 1995), but this may not be comparable to interseeded sorghum species in a field setting and requires additional research before a conclusion can be made.

More recent studies show some evidence of success in perennial grasses which have been established >5 years. In humid environments, sudangrass, forage sorghum, and sorghum-sudangrass consistently increased forage production when interseeded into both smooth bromegrass and tall fescue but the degree of increase depended on harvest

frequency and precipitation after interseeding. In the eastern Nebraska location, if only cut once, sorghum-sudangrass had the highest forage yield but if cut twice, sudangrass was clearly the better option. In many cases, summertime forage yields were doubled in the presence of warm season annual grass interseeding (Guretzky et al., 2020). In addition, total CP yields were 61-103% greater and IVOMD yields were 85-244% greater when interseeded by sudangrass or sorghum-sudangrass, with the one cut after interseeding system having consistently higher nutrient yields than the two cutting system (Guretzky et al., 2021). Regardless of how often you cut, this example shows that it is possible to increase animal gain per unit area by sod-seeding sudangrass and sorghum-sudangrass with the caveat that before interseeding, biomass should be removed as quickly as possible during elongation stages (e.g. producing green chop or haylage) or face incomparable results.

Looking to move towards interseeding in grazed pastures rather than producing stored forages, Guretzky et al. (2023) heavily grazed steers on vegetative smooth brome grass two times before interseeding sorghum-sudangrass and reported an increase in summer of only 36%. It was hypothesized that this difference might be made up for by using a chemical suppressant after grazing so in a similar study, Jenkins et al. (2024; in review) applied different rates of glyphosate to smooth brome grass pastures after two heavy grazing periods and found no benefit to summer forage production interseeding sorghum-sudangrass with this method. Further research may reveal different opportunities for interseeding warm season annual forages into cool season perennial pastures, but until then, it is only suggested to interseed directly after a forage harvest

when the plant will be stunted. Even then, proceed with caution as this was also found to fail multiple years in a row (Jenkins et al., 2024).

N Fertilization vs Legume mixes

Since the invention of the Haber-Bosch method to produce industrial N fertilizer in the early 1900's, agricultural practitioners have relied on synthetic N to increase productivity in annual forage systems. One issue with N fertilization is that the cost is closely linked to fuel cost, as the process itself requires 400-500 °C temperatures and the hydrogen gas used takes 850-900 °C to produce, and are responsible for >1% of global greenhouse gas emissions (Erisman et al., 2008; Smith et al., 2020). For these reasons, finding alternatives to synthetic N fertilizer holds a potential to reduce production costs and consequently, cost of gain.

Among species in the fabaceae family, symbiotic N fixation is the process by which a species-specific rhizobia bacteria infects a host plant, converts gaseous N₂ into ammonium, and in exchange, the plant provides an anaerobic and carbohydrate rich environment to fuel the bacterial enzyme, nitrogenase (Mylona et al., 1995). This agreement between plant and microbe gives legumes the advantage of growing in low N environments, but also enhances the soil environment in several ways. Perennial grass-legume mixtures with no N fertilization see a yield benefit after about a year, especially in dry environments (Foster et al., 2014). In mixed perennial grass-legume hayfields cut several times per year, N acquisition by grasses has been shown to increase with increasing legumes but total N yields by forage were benefited until up to 40-60% legumes were present (Nyfeler et al., 2011). In a preceding study, it was found that mixtures can cause 'transgressive overyielding' effects, which ultimately means they can

increase forage yields above monoculture grass levels. Under 50 kg N ha⁻¹, they saw mixtures with 50-70% legume produce as much as grass monocultures fertilized with 450 kg N ha⁻¹ (Nyfeler et al., 2009). Benefits to total forage yield (Zemenchik et al., 2001) and nutritive value (Zemenchik and Albrecht, 2002) by some perennial legumes have even been quantified and regressed to estimate N replacement values and milk production. These studies indicate that N fertilization in perennial grasses can be replaced by forage legumes, and can even incur additional benefit above N fertilization without N cycling by grazing animals.

In pasture-based dairy systems, including white clover with perennial ryegrass reduced the requirement for N fertilization and was able to produce a greater quantity of milk than monoculture perennial ryegrass pastures with 100 kg N ha⁻¹ of additional fertilizer (Egan et al., 2018). In tall fescue and meadow fescue pastures seeded with white clover, crossbred steer gains increased by 100 kg ha⁻¹ above levels of fertilized monocultures; even though white clover diminished from 41-44% of total DM at the beginning of the trial to 7-18% of total DM in year 3 (Schaefer et al., 2014). In these studies, however, the increased animal performance was not due to overyielding of the grass-legume mixtures, as mixed pastures actually tended to contain less forage mass than N fertilized pastures.

Indeed, part of the advantage of N fixation is that the plant now has access to as much ammonium to use for amino acid production as it wants to pay for in photosynthates, creating a high proportion of N in the plant. Crude protein determination is a method of estimating the protein concentration in ruminant feedstuffs for the purpose of forming a diet ration, based on a standardized calculation of %N x 6.25, and crude

protein in the diet is especially crucial for growing and lactating animals (Licitra et al., 1996; von Keyserlingk et al., 1996). Generally speaking, having high crude protein associated with plant tissues tends to increase animal performance and if that N source is inexpensive, profitability of that system should also be improved.

While there is convincing evidence of this phenomena in perennial grass-legume mixtures, the success of annual grass-legume systems compared to fertilized annual grass monocultures tends to be more blurred by a lack of research. One 3-year study in central Oklahoma grazing stockers on cereal rye/annual ryegrass mixtures with either N fertilization or mixed with 3 cold tolerant legumes, showed that there was no benefit in gain (407 and 373 kg ha⁻¹, respectively) nor net returns (\$282 and \$230 ha⁻¹, respectively) by including legumes (Butler et al., 2012). Ultimately, they concluded that the cost of legume seed was too high to replace the yield and quality benefits of N fertilization, as N fertilization increases tissue N concentrations in forage grasses (Zemenchik and Albrecht, 2002). In summer annual mixtures, we also consistently see reduced total biomass as legume plant density increases within a mixture, even at relatively low N application rates (Bybee-Finley et al., 2016). More multi-year studies on annual forage grass-legume mixtures should be done before concluding against or in favor of including a legume in an annual system.

Conclusion

In conclusion, annual forages can be used to supplement a perennial forage system by providing nutritious forage when typical pasture systems are not productive in the midwestern U.S. In the summer, sorghum and millet species are highly productive forages but when selecting a variety, practitioners should consider environmental

conditions, N management, and palatability (including toxicity). Winter cereal grains can be used as a high quality forage source, especially during early spring months before cool-season perennial pastures are available, or to allow perennial pastures to accumulate forage mass before stocking. In late fall and winter, late summer or fall planted spring grains and brassicas can provide high quality forage to growing or lactating animals. Additionally, a double-cropped annual forage system may be able to provide forage during multiple seasons when forage production in perennial pastures is reduced.

Literature cited

- Akin, D.E., and D. Burdick. 1975. Percentage of Tissue Types in Tropical and Temperate Grass Leaf Blades and Degradation of Tissues by Rumen Microorganisms¹. *Crop Sci.* 15(5): crops1975.0011183X001500050015x. doi: 10.2135/crops1975.0011183X001500050015x.
- Akin, D.E., J.R. Wilson, and W.R. Windham. 1983. Site and Rate of Tissue Digestion in Leaves of C₃, C₄, and C₃/C₄ Intermediate Panicum Species¹. *Crop Sci.* 23(1): crops1983.0011183X002300010042x. doi: 10.2135/crops1983.0011183X002300010042x.
- Allen, V.G., C. Batello, E.J. Berretta, J. Hodgson, M. Kothmann, et al. 2011. An international terminology for grazing lands and grazing animals. *Grass Forage Sci.* 66(1): 2–28. doi: 10.1111/j.1365-2494.2010.00780.x.
- Anderson, V., B. Ilse, and C. Engel. 2014. Drylot vs. pasture beef cow/calf production.
- Andrews, D.J., and K.A. Kumar. 1992. Pearl Millet for Food, Feed, and Forage. In: Sparks, D.L., editor, *Advances in Agronomy*. Academic Press. p. 89–139
- Belesky, D.P., S.R. Wilkinson, R.N. Dawson, and J.E. Elsner. 1981. Forage Production of a Tall Fescue Sod Intercropped with Sorghum × Sudangrass and Rye¹. *Agron. J.* 73(4): 657–660. doi: 10.2134/agronj1981.00021962007300040021x.

- Bhattarai, B., S. Singh, C.P. West, G.L. Ritchie, and C.L. Trostle. 2020a. Effect of deficit irrigation on physiology and forage yield of forage sorghum, pearl millet, and corn. *Crop Sci.* 60(4): 2167–2179. doi: 10.1002/csc2.20171.
- Bhattarai, B., S. Singh, C.P. West, G.L. Ritchie, and C.L. Trostle. 2020b. Water Depletion Pattern and Water Use Efficiency of Forage Sorghum, Pearl millet, and Corn Under Water Limiting Condition. *Agric. Water Manag.* 238: 106206. doi: 10.1016/j.agwat.2020.106206.
- Bragg, T.B., and D.M. Sutherland. 1989. Establishing Warm-Season Grasses and Forbs Using Herbicides and Mowing. *Proc. North Am. Prairie Conf.*
<https://digitalcommons.unl.edu/napcproceedings/7>.
- Brinton, M.M., B.H. Hansen, K.M. Ulmer, Z.E. Carlson, F.H. Hilscher, et al. 2019. Forage production and calf gains when grazing oats following corn harvest. *Transl. Anim. Sci.* 3(Supplement_1): 1641–1645. doi: 10.1093/tas/txz046.
- Brown, R.H. 1978. A Difference in N Use Efficiency in C3 and C4 Plants and its Implications in Adaptation and Evolution¹. *Crop Sci.* 18(1):
crops1978.0011183X001800010025x. doi:
10.2135/crops1978.0011183X001800010025x.
- Brown, R.H. 1985. Growth of C3 and C4 Grasses Under Low N Levels¹. *Crop Sci.* 25(6): crops1985.0011183X002500060013x. doi:
10.2135/crops1985.0011183X002500060013x.

- Bruckner, P.L., and P.L. Raymer. 1990. Factors Influencing Species and Cultivar Choice of Small Grains for Winter Forage. *J. Prod. Agric.* 3(3): 349–355. doi: 10.2134/jpa1990.0349.
- Butler, T.J., J.T. Biermacher, M.K. Kering, and S.M. Interrante. 2012. Production and Economics of Grazing Steers on Rye–Annual Ryegrass with Legumes or Fertilized with Nitrogen. *Crop Sci.* 52(4): 1931–1939. doi: 10.2135/cropsci2011.11.0611.
- Buxton, D.R., I.C. Anderson, and A. Hallam. 1998. Intercropping Sorghum into Alfalfa and Reed Canarygrass to Increase Biomass Yield. *J. Prod. Agric.* 11(4): 481–486. doi: 10.2134/jpa1998.0481.
- Buxton, D.R., I.C. Anderson, and A. Hallam. 1999. Performance of Sweet and Forage Sorghum Grown Continuously, Double-Cropped with Winter Rye, or in Rotation with Soybean and Maize. *Agron. J.* 91(1): 93–101. doi: 10.2134/agronj1999.00021962009100010015x.
- Bybee-Finley, K.A., S.B. Mirsky, and M.R. Ryan. 2016. Functional Diversity in Summer Annual Grass and Legume Intercrops in the Northeastern United States. *Crop Sci.* 56(5): 2775–2790. doi: 10.2135/cropsci2016.01.0046.
- Campbell, B.J., C.H. Gelley, J.S. McCutcheon, F.L. Fluharty, and A.J. Parker. 2021. A comparison of annual forages and stockpiled pasture on the growth and health parameters of grazing fall-born lambs. *Small Rumin. Res.* 196: 106335. doi: 10.1016/j.smallrumres.2021.106335.

- Chung, I.-M., and D.A. Miller. 1995. Allelopathic Influence of Nine Forage Grass Extracts on Germination and Seedling Growth of Alfalfa. *Agron. J.* 87(4): 767–772. doi: 10.2134/agronj1995.00021962008700040026x.
- Collatz, G.J., M. Ribas-Carbo, and J.A. Berry. 1992. Coupled Photosynthesis-Stomatal Conductance Model for Leaves of C4 Plants. *Funct. Plant Biol.* 19(5): 519–538. doi: 10.1071/pp9920519.
- Contreras-Govea, F.E., D.M. VanLeeuwen, S.V. Angadi, and M.A. Marsalis. 2013. Enhances in Crude Protein and Effects on Fermentation Profile of Corn and Forage Sorghum Silage with Addition of Cowpea. *Forage Grazinglands* 11(1): 1–7. doi: 10.1094/FG-2013-0622-01-RS.
- Conway, A., R. Bondurant, F. Hilscher, J. Parsons, D. Redfearn, et al. 2019. Impact of Grazing Spring Rye on Subsequent Crop Yields and Profitability. *Neb. Beef Cattle Rep.* <https://digitalcommons.unl.edu/animalscinbcr/1034>.
- Cooper-Driver, G., S. Finch, T. Swain, and E. Bernays. 1977. Seasonal variation in secondary plant compounds in relation to the palatability of *Pteridium aquilinum*. *Biochem. Syst. Ecol.* 5(3): 177–183. doi: 10.1016/0305-1978(77)90002-3.
- Cornic, G., and J.-M. Briantais. 1991. Partitioning of photosynthetic electron flow between CO₂ and O₂ reduction in a C₃ leaf (*Phaseolus vulgaris* L.) at different CO₂ concentrations and during drought stress. *Planta* 183(2): 178–184. doi: 10.1007/BF00197786.

- Creel, R.J., and H.A. Fribourg. 1981. Interactions between Forage Sorghum Cultivars and Defoliation Managements¹. *Agron. J.* 73(3): 463–469. doi: 10.2134/agronj1981.00021962007300030018x.
- Cunningham, M.D., and W.W. Ragland. 1971. Plant Composition and Feeding Value of Sudangrass and Sorghum-Sudangrass in a Controlled Grazing System¹, 2. *J. Dairy Sci.* 54(10): 1461–1464. doi: 10.3168/jds.S0022-0302(71)86047-2.
- Denison, R.F., and H.D. Perry. 1990. Seasonal Growth Rate Patterns for Orchardgrass and Tall Fescue on the Appalachian Plateau. *Agron. J.* 82(5): 869–873. doi: 10.2134/agronj1990.00021962008200050004x.
- Drewnoski, M., J. Parsons, H. Blanco, D. Redfearn, K. Hales, et al. 2018. Forages and pastures symposium: cover crops in livestock production: whole-system approach. Can cover crops pull double duty: conservation and profitable forage production in the Midwestern United States? *J. Anim. Sci.* 96(8): 3503–3512. doi: 10.1093/jas/sky026.
- Druille, M., A.S. Williams, M. Torrecillas, S. Kim, N. Meki, et al. 2020. Modeling Climate Warming Impacts on Grain and Forage Sorghum Yields in Argentina. *Agronomy* 10(7): 964. doi: 10.3390/agronomy10070964.
- Egan, M., N. Galvin, and D. Hennessy. 2018. Incorporating white clover (*Trifolium repens* L.) into perennial ryegrass (*Lolium perenne* L.) swards receiving varying levels of nitrogen fertilizer: Effects on milk and herbage production. *J. Dairy Sci.* 101(4): 3412–3427. doi: 10.3168/jds.2017-13233.

- Ehleringer, J., and O. Björkman. 1977. Quantum Yields for CO₂ Uptake in C₃ and C₄ Plants: Dependence on Temperature, CO₂, and O₂ Concentration. *Plant Physiol.* 59(1): 86–90. doi: 10.1104/pp.59.1.86.
- Ehleringer, J.R., and R.K. Monson. 1993. Evolutionary and Ecological Aspects of Photosynthetic Pathway Variation. *Annu. Rev. Ecol. Syst.* 24: 411–439.
- Erisman, J.W., M.A. Sutton, J. Galloway, Z. Klimont, and W. Winiwarter. 2008. How a century of ammonia synthesis changed the world. *Nat. Geosci.* 1(10): 636–639. doi: 10.1038/ngeo325.
- Farquhar, G.D., and T.D. Sharkey. 1982. Stomatal Conductance and Photosynthesis. *Annu. Rev. Plant Physiol.* 33(1): 317–345. doi: 10.1146/annurev.pp.33.060182.001533.
- Foster, A., C.L. Vera, S.S. Malhi, and F.R. Clarke. 2014. Forage yield of simple and complex grass–legume mixtures under two management strategies. *Can. J. Plant Sci.* 94(1): 41–50. doi: 10.4141/cjps2013-095.
- Fouli, Y., S.W. Duiker, D.D. Fritton, M.H. Hall, J.E. Watson, et al. 2012. Double cropping effects on forage yield and the field water balance. *Agric. Water Manag.* 115: 104–117. doi: 10.1016/j.agwat.2012.08.014.
- Funston, R.N., and D.M. Larson. 2011. Heifer development systems: Dry-lot feeding compared with grazing dormant winter forage1. *J. Anim. Sci.* 89(5): 1595–1602. doi: 10.2527/jas.2010-3095.

- Gelley, C., R.L.G. Nave, and G. Bates. 2016. Forage Nutritive Value and Herbage Mass Relationship of Four Warm-Season Grasses. *Agron. J.* 108(4): 1603–1613. doi: 10.2134/agronj2016.01.0018.
- Gettle, R.M., J.R. George, K.M. Blanchet, K.J. Moore, and D.R. Buxton. 1996. Frost-Seeding Legumes into Established Switchgrass: Establishment, Density, Persistence, and Sward Composition. *Agron. J.* 88(1): 98–103. doi: 10.2134/agronj1996.00021962008800010021x.
- Ghannoum, O. 2009. C4 photosynthesis and water stress. *Ann. Bot.* 103(4): 635–644. doi: 10.1093/aob/mcn093.
- Glamoclija, D., S. Jankovic, S. Rakic, R. Maletic, J. Ikanovic, et al. 2011. Effects of nitrogen and harvesting time on chemical composition of biomass of Sudan grass, fodder sorghum, and their hybrid. *Turk. J. Agric. For.* 35(2): 127–138. doi: 10.3906/tar-0911-58.
- Gleadow, R.M., M.J. Ottman, B.A. Kimball, G.W. Wall, P.J. Pinter, et al. 2016. Drought-induced changes in nitrogen partitioning between cyanide and nitrate in leaves and stems of sorghum grown at elevated CO₂ are age dependent. *Field Crops Res.* 185: 97–102. doi: 10.1016/j.fcr.2015.10.010.
- Grant, T.A., T.L. Shaffer, and B. Flanders. 2020. Patterns of Smooth Brome, Kentucky Bluegrass, and Shrub Invasion in the Northern Great Plains Vary with Temperature and Precipitation. *Nat. Areas J.* 40(1): 11–22. doi: 10.3375/043.040.0103.

- Guretzky, J.A., K.R. Harmony, J.L. Moyer, J.D. Volesky, and M.B. Stephenson. 2021. Interseeding annual warm-season grasses into pastures: Forage nutritive value and yields. *Agron. J.* 113(3): 2544–2556. doi: 10.1002/agj2.20653.
- Guretzky, J.A., J.D. Volesky, M.B. Stephenson, K.R. Harmony, and J.L. Moyer. 2020. Interseeding annual warm-season grasses into temperate pasturelands: Forage accumulation and composition. *Agron. J.* 112(4): 2812–2825. doi: 10.1002/agj2.20250.
- Haskins, F.A., H.J. Gorz, and B.E. Johnson. 1987. Seasonal Variation in Leaf Hydrocyanic Acid Potential of Low- and High-Dhurrin Sorghums¹. *Crop Sci.* 27(5): crops1987.0011183X002700050014x. doi: 10.2135/crops1987.0011183X002700050014x.
- Hastert, A.A., C.E. Owensby, and L.H. Harbers. 1983. Rumen Microbial Degradation of Indiangrass and Big Bluestem Leaf Blades¹. *J. Anim. Sci.* 57(6): 1626–1636. doi: 10.2527/jas1983.5761626x.
- Hill, G.M., P.R. Utley, and W.C. McCormick. 1985. Evaluation of Cow-Calf Systems Using Ryegrass Sod-Seeded in Perennial Pastures. *J. Anim. Sci.* 61(5): 1088–1094. doi: 10.2527/jas1985.6151088x.
- Hitz, A.C., and J.R. Russell. 1998. Potential of stockpiled perennial forages in winter grazing systems for pregnant beef cows³. *J. Anim. Sci.* 76(2): 404–415. doi: 10.2527/1998.762404x.

- Holman, J.D., A. Schlegel, A.K. Obour, and Y. Assefa. 2020. Dryland cropping system impact on forage accumulation, nutritive value, and rainfall use efficiency. *Crop Sci.* 60(6): 3395–3409. doi: 10.1002/csc2.20251.
- Ibrahim, M., M. Ayub, A. Tanveer, and M. Yaseen. 2012. Forage quality of maize and legumes as monocultures and mixtures at different seed ratios. *JAPS J. Anim. Plant Sci.* 22(4): 987–992.
- Islam, M.A., J.T. Biermacher, S.M. Interrante, R.R. Reuter, A.A. Hopkins, et al. 2011. Production and Economics of Grazing Rye—Annual Ryegrass and Tall Fescue Systems. *Agron. J.* 103(2): 558–564. doi: 10.2134/agronj2010.0325.
- Jensen, E.F., M.D. Casler, K. Farrar, J.M. Finnan, R. Lord, et al. 2018. 5 - Reed Canary Grass: From Production to End Use. In: Alexopoulou, E., editor, *Perennial Grasses for Bioenergy and Bioproducts*. Academic Press. p. 153–173
- Jones, D. 2007. Cyanogenesis in Animal—Plant Interactions - Jones - Novartis Foundation Symposia - Wiley Online Library.
<https://onlinelibrary.wiley.com/doi/abs/10.1002/9780470513712.ch10> (accessed 25 August 2023).
- Kallenbach, R.L., G.J. Bishop-Hurley, M.D. Massie, M.S. Kerley, and C.A. Roberts. 2003. Stockpiled Annual Ryegrass for Winter Forage in the Lower Midwestern USA. *Crop Sci.* 43(4): 1414–1419. doi: 10.2135/cropsci2003.1414.
- Kallenbach, R.L., M.S. Kerley, and G.J. Bishop-Hurley. 2006. Cumulative Forage Production, Forage Quality and Livestock Performance from an Annual Ryegrass

and Cereal Rye Mixture in a Pine Walnut Silvopasture. *Agrofor. Syst.* 66(1): 43–53. doi: 10.1007/s10457-005-6640-6.

Keyser, P., K.E. Zechiel, G. Bates, A.J. Ashworth, R. Nave, et al. 2022. Evaluation of five C4 forage grasses in the tall Fescue Belt. *Agron. J.* 114(6): 3347–3357. doi: 10.1002/agj2.21195.

von Keyserlingk, M.A.G., M.L. Swift, R. Puchala, and J.A. Shelford. 1996. Degradability characteristics of dry matter and crude protein of forages in ruminants. *Anim. Feed Sci. Technol.* 57(4): 291–311. doi: 10.1016/0377-8401(95)00865-9.

Kim, K., S. Webb, M. Newell, J. Anderson, and T. Butler. 2017. Variation of winter forage production in four small grain species: oat, rye, triticale and wheat. *Pak. J. Bot.* 49: 553–559.

Kindiger, B. 1993. A method to enhance germination of Eastern gamagrass. *Maydica* 39: 53–56.

Koch, D.W., G.W. Mueller-Warrant, and New Hampshire Agricultural Experiment Station. 1983. Sod seeding of forages, *Station Bulletin*, no.525.

Krueger, E.S., T.E. Ochsner, J.M. Baker, P.M. Porter, and D.C. Reicosky. 2012. Rye–Corn Silage Double-Cropping Reduces Corn Yield but Improves Environmental Impacts. *Agron. J.* 104(4): 888–896. doi: 10.2134/agronj2011.0341.

- Ku, S.-B., and G.E. Edwards. 1977a. Oxygen Inhibition of Photosynthesis: II. Kinetic Characteristics as Affected by Temperature 1. *Plant Physiol.* 59(5): 991–999. doi: 10.1104/pp.59.5.991.
- Ku, S.-B., and G.E. Edwards. 1977b. Oxygen Inhibition of Photosynthesis: I. Temperature Dependence and Relation to O₂/CO₂ Solubility Ratio 1. *Plant Physiol.* 59(5): 986–990. doi: 10.1104/pp.59.5.986.
- Kumar, R., H.A. Lardner, J.J. McKinnon, D.A. Christensen, D. Damiran, et al. 2012. Comparison of alternative backgrounding systems on beef calf performance, feedlot finishing performance, carcass traits, and system cost of gain¹. *Prof. Anim. Sci.* 28(5): 541–551. doi: 10.15232/S1080-7446(15)30403-4.
- Kunelius, H.T., M.R. Carter, J. Kimpinski, and J.B. Sanderson. 1988. Effect of seeding method on alfalfa and red clover establishment and growth, soil physical condition and nematode populations. *Soil Tillage Res.* 12(2): 163–175. doi: 10.1016/0167-1987(88)90039-6.
- Lauriault, L.M., L.H. Schmitz, S.H. Cox, and E.J. Scholljegerdes. 2021. A Comparison of Pearl Millet and Sorghum–Sudangrass Pastures during the Frost-Prone Autumn for Growing Beef Cattle in Semiarid Region. *Agriculture* 11(6): 541. doi: 10.3390/agriculture11060541.
- Lawson, T., and J. Matthews. 2020. Guard Cell Metabolism and Stomatal Function. *Annu. Rev. Plant Biol.* 71(1): 273–302. doi: 10.1146/annurev-arplant-050718-100251.

- Lehmkuhler, J. 2011. Strategies for Reducing Losses to Forage Related Disorders. Forage Symp. Ky. Cattlemen's Conv.
https://uknowledge.uky.edu/forage_kca/2011/Session/4.
- Lenz, M.E., J.L. Cox-O'Neill, K.E. Hales, and M.E. Drewnoski. 2019. Nutritive Value Change during the Fall of Late-Summer-Planted Oats, Radishes, and Turnips. *Crop Forage Turfgrass Manag.* 5(1): 180097. doi: 10.2134/cftm2018.12.0097.
- Li, Y., V.G. Allen, F. Hou, J. Chen, and C.P. Brown. 2013. Steers Grazing a Rye Cover Crop Influence Growth of Rye and No-Till Cotton. *Agron. J.* 105(6): 1571–1580. doi: 10.2134/agronj2013.0020.
- Licitra, G., T.M. Hernandez, and P.J. Van Soest. 1996. Standardization of procedures for nitrogen fractionation of ruminant feeds. *Anim. Feed Sci. Technol.* 57(4): 347–358. doi: 10.1016/0377-8401(95)00837-3.
- Lin, C.H., R.L. McGraw, M.F. George, and H.E. Garrett. 1998. Shade effects on forage crops with potential in temperate agroforestry practices. *Agrofor. Syst.* 44(2): 109–119. doi: 10.1023/A:1006205116354.
- Maciel, I.C.F., L.R. Thompson, R.M. Martin, K.A. Cassida, J.P. Schwehofer, et al. 2022. Effects of annual small grain–brassica forage mixtures during the last 70 days of the forage-finishing period on: I. Forage production, beef steer performance, and carcass characteristics. *Appl. Anim. Sci.* 38(3): 222–236. doi: 10.15232/aas.2021-02245.

- Maloney, T.S., E.S. Oplinger, and K.A. Albrecht. 1999. Small Grains for Fall and Spring Forage. *J. Prod. Agric.* 12(3): 488–494. doi: 10.2134/jpa1999.0488.
- McCartney, D., J.A. Basarab, E.K. Okine, V.S. Baron, and A.J. Depalme. 2004. Alternative fall and winter feeding systems for spring calving beef cows. *Can. J. Anim. Sci.* 84(3): 511–522. doi: 10.4141/A03-069.
- Mitchell, R.B., and C.M. Britton. 2000. Managing Weeds to Establish and Maintain Warm-Season Grasses. *Native Warm-Season Grasses: Research Trends and Issues.* John Wiley & Sons, Ltd. p. 159–176
- Moser, L.E., and C.S. Hoveland. 1996. Cool-Season Grass Overview. *Cool-Season Forage Grasses.* John Wiley & Sons, Ltd. p. 1–14
- Mousel, E.M., W.H. Schacht, C.W. Zanner, and L.E. Moser. 2005. Effects of Summer Grazing Strategies on Organic Reserves and Root Characteristics of Big Bluestem. *Crop Sci.* 45(5): 2008–2014. doi: 10.2135/cropsci2004.0694.
- Mylona, P., K. Pawlowski, and T. Bisseling. 1995. Symbiotic Nitrogen Fixation. *Plant Cell* 7(7): 869–885.
- Nyfeler, D., O. Huguenin-Elie, M. Suter, E. Frossard, J. Connolly, et al. 2009. Strong mixture effects among four species in fertilized agricultural grassland led to persistent and consistent transgressive overyielding. *J. Appl. Ecol.* 46(3): 683–691. doi: 10.1111/j.1365-2664.2009.01653.x.

- Nyfeler, D., O. Huguenin-Elie, M. Suter, E. Frossard, and A. Lüscher. 2011. Grass–legume mixtures can yield more nitrogen than legume pure stands due to mutual stimulation of nitrogen uptake from symbiotic and non-symbiotic sources. *Agric. Ecosyst. Environ.* 140(1): 155–163. doi: 10.1016/j.agee.2010.11.022.
- Oaks, A. 1994. Efficiency of Nitrogen Utilization in C3 and C4 Cereals. *Plant Physiol.* 106(2): 407–414.
- Ogren, W.L. 1984. Photorespiration: Pathways, Regulation, and Modification. *Annu. Rev. Plant Physiol.* 35(1): 415–442. doi: 10.1146/annurev.pp.35.060184.002215.
- Ottman, M., and A. Mostafa. 2014. Summer Slump in Alfalfa. *CALS Publ. Arch. Univ. Ariz.* <https://repository.arizona.edu/handle/10150/311219> (accessed 9 January 2023).
- Ozeki, K., Y. Miyazawa, and D. Sugiura. 2022. Rapid stomatal closure contributes to higher water use efficiency in major C4 compared to C3 Poaceae crops. *Plant Physiol.* 189(1): 188–203. doi: 10.1093/plphys/kiac040.
- Pembleton, K.G., B.R. Cullen, R.P. Rawnsley, M.T. Harrison, and T. Ramilan. 2016. Modelling the resilience of forage crop production to future climate change in the dairy regions of Southeastern Australia using APSIM. *J. Agric. Sci.* 154(7): 1131–1152. doi: 10.1017/S0021859615001185.
- Pembleton, K.G., B.R. Cullen, R.P. Rawnsley, T. Ramilan, K.G. Pembleton, et al. 2020. Climate change effects on pasture-based dairy systems in south-eastern Australia. *Crop Pasture Sci.* doi: 10.1071/CP20108.

- Peterhansel, C., I. Horst, M. Niessen, C. Blume, R. Kebeish, et al. 2010. Photorespiration. Arab. Book 2010(8). doi: 10.1199/tab.0130.
- Phillips, H.N., B.J. Heins, K. Delate, and R. Turnbull. 2021. Biomass Yield and Nutritive Value of Rye (*Secale cereale* L.) and Wheat (*Triticum aestivum* L.) Forages While Grazed by Cattle. *Crops* 1(2): 42–53. doi: 10.3390/crops1020006.
- Plastina, A., J. Acharya, F.M. Marcos, M.R. Parvej, M.A. Licht, et al. 2023. Does grazing winter cereal rye in Iowa, USA, make it profitable? *Renew. Agric. Food Syst.* 38: e45. doi: 10.1017/S1742170523000388.
- Power, J.F. 1988. Seasonal Changes in Smooth Bromegrass Top and Root Growth and Fate of Fertilizer Nitrogen. *Agron. J.* 80(5): 740–745. doi: 10.2134/agronj1988.00021962008000050009x.
- Pupo, M.R., M.O. Wallau, and L.F. Ferraretto. 2022. Effects of season, variety type, and trait on dry matter yield, nutrient composition, and predicted intake and milk yield of whole-plant sorghum forage. *J. Dairy Sci.* 105(7): 5776–5785. doi: 10.3168/jds.2021-21706.
- Rabas, D.L., A.R. Schmid, and G.C. Marten. 1970. Relationship of Chemical Composition and Morphological Characteristics to Palatability in Sudangrass and Sorghum \times Sudangrass Hybrids¹. *Agron. J.* 62(6): 762–763. doi: 10.2134/agronj1970.00021962006200060023x.
- Raines, C.A. 2003. The Calvin cycle revisited. *Photosynth. Res.* 75(1): 1–10. doi: 10.1023/A:1022421515027.

- Redfearn, D.D., B.C. Venuto, W.D. Pitman, M.W. Alison, and J.D. Ward. 2002. Cultivar and Environment Effects on Annual Ryegrass Forage Yield, Yield Distribution, and Nutritive Value. *Crop Sci.* 42(6): 2049–2054. doi: 10.2135/cropsci2002.2049.
- Rice, C.P., B.A. Otte, M. Kramer, H.H. Schomberg, S.B. Mirsky, et al. 2022. Benzoxazinoids in roots and shoots of cereal rye (*Secale cereale*) and their fates in soil after cover crop termination. *Chemoecology* 32(3): 117–128. doi: 10.1007/s00049-022-00371-x.
- Riley, H., K. Hales, S. Shackelford, H. Freetly, and M. Drewnoski. 2019. Effect of Rapeseed Inclusion in Late-Summer Planted Oats Pasture on Growing Performance of Beef Steers. *Neb. Beef Cattle Rep.* <https://digitalcommons.unl.edu/animalscinbcr/1036>.
- Sage, R.F., and D.S. Kubien. 2007. The temperature response of C3 and C4 photosynthesis. *Plant Cell Environ.* 30(9): 1086–1106. doi: 10.1111/j.1365-3040.2007.01682.x.
- Sage, R.F., R.W. Pearcy, and J.R. Seemann. 1987. The Nitrogen Use Efficiency of C3 and C4 Plants 1: III. Leaf Nitrogen Effects on the Activity of Carboxylating Enzymes in *Chenopodium album* (L.) and *Amaranthus retroflexus* (L.). *Plant Physiol.* 85(2): 355–359. doi: 10.1104/pp.85.2.355.
- Schaefer, M.R., K.A. Albrecht, and D.M. Schaefer. 2014. Stocker Steer Performance on Tall Fescue or Meadow Fescue Alone or in Binary Mixture with White Clover. *Agron. J.* 106(5): 1902–1910. doi: 10.2134/agronj14.0075.

- Sedivec, K., A. Fraase, B. Neville, D. Whitted, P. Nyren, et al. 2011. Utilizing Annual Forages in Single and Dual Cropping Systems for Late-Fall and Early Winter Grazing: Impacts on Forage Production, Cow Performance, Soil Health, and Economics.
- Sheaffer, C.C., G.C. Marten, R.M. Jordan, and E.A. Ristau. 1992a. Sheep Performance during Grazing of Annual Forages in a Double Cropping System. *J. Prod. Agric.* 5(1): 33–37. doi: 10.2134/jpa1992.0033.
- Sheaffer, C.C., P.R. Peterson, M.H. Hall, and J.B. Stordahl. 1992b. Drought Effects on Yield and Quality of Perennial Grasses in the North Central United States. *J. Prod. Agric.* 5(4): 556–561. doi: 10.2134/jpa1996.0556.
- Sheaffer, C.C., and D.R. Swanson. 1982. Seeding Rates and Grass Suppression for Sod-seeded Red Clover and Alfalfa. *Agron. J.* 74(2): 355–358. doi: 10.2134/agronj1982.00021962007400020022x.
- Singh, B.R., and D.P. Singh. 1995. Agronomic and physiological responses of sorghum, maize and pearl millet to irrigation. *Field Crops Res.* 42(2): 57–67. doi: 10.1016/0378-4290(95)00025-L.
- Smith, C., A. K. Hill, and L. Torrente-Murciano. 2020. Current and future role of Haber-Bosch ammonia in a carbon-free energy landscape. *Energy Environ. Sci.* 13(2): 331–344. doi: 10.1039/C9EE02873K.

- Swain, F.G., A.M. Decker, and H.J. Retzer. 1965. Sod-Seeding of Annual Forages into 'Midland' Bermudagrass (*Cynodon dactylon* L.) Pastures. I. Species Evaluation I. *Agron. J.* 57(6): 596–598. doi: 10.2134/agronj1965.00021962005700060024x.
- Venuto, B., and B. Kindiger. 2008. Forage and biomass feedstock production from hybrid forage sorghum and sorghum–sudangrass hybrids. *Grassl. Sci.* 54(4): 189–196. doi: 10.1111/j.1744-697X.2008.00123.x.
- Way, D.A., G.G. Katul, S. Manzoni, and G. Vico. 2014. Increasing water use efficiency along the C3 to C4 evolutionary pathway: a stomatal optimization perspective. *J. Exp. Bot.* 65(13): 3683–3693. doi: 10.1093/jxb/eru205.
- Willms, W.D., L.M. Rode, and B.S. Freeze. 1993. Winter performance of Hereford cows on fescue prairie and in drylot as influenced by fall grazing. *Can. J. Anim. Sci.* 73(4): 881–889. doi: 10.4141/cjas93-090.
- Wilson, J.R. 1993. Organization of Forage Plant Tissues. Forage Cell Wall Structure and Digestibility. John Wiley & Sons, Ltd. p. 1–32
- Wilson, J.R., D.E. Akin, M.N. McLEOD, and D.J. Minson. 1989. Particle size reduction of the leaves of a tropical and a temperate grass by cattle. *Grass Forage Sci.* 44(1): 65–75. doi: 10.1111/j.1365-2494.1989.tb01911.x.
- Zemenchik, R.A., and K.A. Albrecht. 2002. Nitrogen Use Efficiency and Apparent Nitrogen Recovery of Kentucky Bluegrass, Smooth Bromegrass, and Orchardgrass. *Agron. J.* 94(3): 421–428. doi: 10.2134/agronj2002.4210.

Zemenchik, R.A., K.A. Albrecht, and M.K. Schultz. 2001. Nitrogen Replacement Values of Kura Clover and Birdsfoot Trefoil in Mixtures with Cool-Season Grasses. *Agron. J.* 93(2): 451–458. doi: 10.2134/agronj2001.932451x.

CHAPTER 2 - HERBAGE ACCUMULATION AND NUTRITIVE VALUE OF A DOUBLE-CROPPED ANNUAL FORAGE SYSTEM AND A DIVERSE PERENNIAL CIRCULAR FORAGE SYSTEM

Abstract

A call for diverse perennial circular forage systems (DPCFS) has recently been issued due to their economic and environmental benefits to cropland. Double cropped annual forage systems (DCAFS) intend to mimic these DPCFS by improving plant diversity while increasing the length of time roots are actively growing in the soil. Additionally, grazing and legume inclusion allows for nutrient cycling to occur. Our study sought to compare herbage mass components, nutritive value, and litter cover in a DPCFS containing smooth brome grass pastures to a DCAFS with winter triticale and pearl millet pastures. Each system contained a N-fertilized treatment and a mixed grass-legume treatment. In the DCAFS, forage species mass, N yield, and IVOMD yield were greatest in the N-fertilized treatment in the summer of 2023 when June and July precipitation was 124.4 mm above the 30-year average. In the summer of 2022, June and July precipitation was 227 mm below the 30-year average which increased forage species N concentration in the N-fertilized treatment and consequently N yield, despite having similar mass. A similar effect was seen in spring forage species when precipitation was low to average in the spring of 2022 and very low in the spring of 2023. In the DPCFS, forage species mass, N yield, and IVOMD yield were greatest in the spring, especially in 2022. In this system, the mixed grass-legume treatment produced similar forage species

mass and IVOMD yield but had a lower N yield compared to the N-fertilized treatment. Litter cover was greatest in the DPCFS and was resistant to change across sampling times. In the DCAFS, litter cover changed across sampling times and more bare soil was exposed. In conclusion, the DCAFS responded to N fertilization in the summer, but only when moisture was adequate.

Introduction

Annual forages are often planted on cropland during seasons when grain crops are not grown to enhance ecosystem services while also providing additional forage resources to livestock (Lemaire et al., 2014). Recently, there has been a push to replace grain cropland with diverse perennial circular systems because of their exceptional agroecological benefits to stability and resilience, ecosystem services, human health, social inclusion, and economic well-being (Picasso et al., 2022). These diverse perennial circular systems are described as having crop diversity with some level of perenniality and a circularity which means that livestock and legumes are utilized to cycle N and other nutrients at the farm-scale rather than importing or exporting nutrients. Perennial grass-legume mixtures with 50-70% legume have been shown to improve forage production above grass monocultures, even those under excessive levels of N fertilization while haying (Nyfeler et al., 2011). Additionally, even small amounts of white clover (*Trifolium repens* L.) in perennial grass pastures have been shown to improve milk yields above N-fertilized pastures in pasture-based dairying systems (Egan et al., 2018) and improve steer gains during backgrounding (Schaefer et al., 2014). In long-term smooth brome grass (*Bromus inermis* Leyss.) pastures, a grass-legume mixture with <15%

remaining legume can even produce greater forage mass than N-fertilized smooth brome grass (Guretzky et al., 2023).

Litter leftover from plant residues is a vital component of soil C and N dynamics. It has been shown to be labile and available as a microbial substrate, contributing a large degree towards nutrient cycling (Liu et al., 2010; Yang et al., 2022) and a smaller degree to organic matter stabilization in surface soils (Witzgall et al., 2021). In a comparison between smooth brome grass, meadow brome grass (*Bromus biebersteinii* Roem. & Schult. [excluded]), and triticale (\times *Triticosecale* Wittm. ex A. Camus [*Secale* \times *Triticum*]), smooth brome grass always had greater litter mass in the fall than triticale pastures and supplied the greatest C and N yields back to the soil (Mapfumo et al., 2002). In perennial meadows, organic matter was found to be highest in larger aggregate sizes compared to a spring cereal grain cropping system (Semenov et al., 2020) and likely indicates better soil structure and more and larger particulate organic matter is available for microbial interaction from perennial litter and root mass. Maintaining litter cover with crop residues is crucial for resisting soil sediment removal even in long-term no-tillage systems. Just one litter removal event by baling can increase erosion into the following year compared to no residue removal and tilling crop residues will increase sediment losses even more (Wilson et al., 2004). Maintaining litter cover also benefits the water cycle in soils by reducing rainfall kinetic energy which reduces surface compacting and maintains water infiltration capacity, holds water in the soil physically and through temperature buffering, and can aid in catching and holding snow (Smika and Unger, 1986).

Research on soil physicochemical properties comparing annual and perennial systems has recently been initiated. However, less is known about differences between diverse perennial circular systems and annual systems. Mapfumo et al. (2002) suggests grazing intensity plays a dynamic role in organic matter stabilization as light grazing ubiquitously produced greater litter mass than moderate and heavy grazing systems and shifting from light to moderate grazing seemed to stimulate root growth as root mass to a depth of 60 cm increased by 19% for smooth brome grass and 29% for triticale, although smooth brome grass always had 2.67- to 3-fold greater root mass than triticale at these intensities. Because of the reduced litter mass, increasing grazing intensity increases bare ground occurrences in pastures (Naeth et al., 1991).

In addition to soil and litter differences, other differences exist between these two types of systems including forage accumulation, distribution, nutritive value, animal performance, and costs. In a 5-year study grazing a mixture of cereal rye and annual ryegrass compared to a novel endophyte tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.) pasture, total weight gains were greater in the annual mixture (491 kg ha⁻¹) than the perennial pasture (349 kg ha⁻¹) and the annual mixture was able to be grazed for 63 more days ha⁻¹. However, the annual pasture had greater total costs and ultimately similar net return to tall fescue (Islam et al., 2011). In this study, tall fescue seeding costs were amortized over 5 years and if amortized for longer, net returns would become greater for tall fescue, as was seen in previous research (Beck et al., 2008). In double-cropped annual forage systems, there is an opportunity to further increase forage production and distribution by having cool-season annual production in the late fall and spring and warm-season annual production in the summer and early fall. This was seen in

cereal rye (*Secale cereale* L.)/forage sorghum (*Sorghum bicolor* (L.) Moench) (Buxton et al., 1999) and winter triticale/forage sorghum double crop systems (Holman et al., 2020).

Because double-cropped annual forages seem to be productive and well distributed, one objective of this study was to compare seasonal forage accumulation and nutritive value of a double-cropped annual forage system to a diverse perennial circular system. In addition, we wanted to observe how soil litter cover changed throughout the season between these two systems since previous literature has only compared smooth brome grass pastures to triticale pastures without double cropping a summer annual forage. Our third objective was to compare the effects of N fertilization with unfertilized mixed grass-legume treatments on herbage component mass and nutritive value.

Materials and Methods

Site History

The diverse perennial circular forage system (DPCFS) and the double cropped annual forage system (DCAFS) experiments were conducted near Mead, NE at the University of Nebraska – Lincoln Eastern Nebraska Research, Extension, and Education Center in 2022-2023. In 1981, the site for the DPCFS experiment was seeded with ‘Lincoln’ smooth brome grass, and six adjacent 1.20-ha pastures were established. From 1985 to 2009 these pastures were fertilized annually with 90 kg N ha⁻¹ urea in March or April. In 2010 three random pastures were selected and interseeded with a diverse legume mixture including alfalfa (*Medicago sativa* L.), red clover (*Trifolium pratense* L.), and birdsfoot trefoil (*Lotus corniculatus* L.), as a replacement for N fertilization in those pastures. From 2012 to this study, each of the six pastures was rotationally stocked with 2.5 to 3.3 variably sized crossbred steers (*Bos taurus* L.) ha⁻¹ using six or twelve equally

sized paddocks. In depth management history was provided in Guretzky et al., (2023) and Jenkins et al., (2024). Since the time of seeding, pastures have become more diverse with perennial grasses including creeping foxtail (*Alopecurus arundinaceus* Poir.), reed canarygrass (*Phalaris arundinacea* L.), and Kentucky bluegrass (*Poa pratensis* L.); though smooth bromegrass remains the dominant component of the cool season grass community. Soils in the DPCFS experiment consisted of 30% Yutan silty clay loam (fine-silty, mixed, superactive, mesic Mollic Hapludalfs), 51% Tomek silt loam (fine, smectitic, mesic, Pachic Argiudolls), and 19% Filbert silt loam (fine, smectitic, mesic Vertic Argialbolls).

The DCAFS experiment was established on a site that historically had been used for corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production. Beginning in fall 2019, the DCAFS experiment was established by seeding nine, 0.4-ha pastures to triticale [\times *Triticosecale* Wittm. ex A. Camus (*Secale* \times *Triticum*)]. In spring, three of the triticale pastures were interseeded with red clover (*Trifolium pratense* L.), three were fertilized with N, and three remained non-fertilized. After a spring grazing period, the pastures were terminated, and a summer crop of sorghum-sudangrass [*Sorghum bicolor* (L.) Moench \times *S. bicolor* (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan] was seeded. After cutting and removing the crop as hay in late summer, the triticale-summer annual forage sequence was repeated in 2020-2021, 2021-2022, and 2022-2023 except pearl millet (*Pennisetum glaucum* (L.) R. Br.) was substituted for sorghum-sudangrass, and forage soybean (*Glycine max* (L.) Merr.) was added to the three pastures with the mixed-legume component. Thus, the triticale-red clover mixture was double cropped with a pearl millet-soybean mixture in the mixed-legume pasture

treatment. In the N-fertilized treatment, the three fertilized triticale pastures received 67 kg N ha⁻¹ as granular urea in spring from 2020-2023. The pearl millet that followed the fertilized triticale pastures also received 67 kg N ha⁻¹ in summer 2021-2023, but sorghum-sudangrass did not receive any in summer 2020. The mixed-legume and non-fertilized pastures did not receive any fertilizer from 2020-2023. Soils in the DCAFS experiment consisted of 30% Yutan silty clay loam, 34% Fillmore silt loam (fine, smectitic, mesic Vertic Argialbolls), and 36% Filbert silt loam.

Experimental Design

In this study, a common set of data collected from the 2021-2022 and 2022-2023 production seasons were used to evaluate the effects of N fertilizer versus seeding legumes in the DPCFS and DCAFS experiments. The DPCFS experiment had a completely randomized design with three replications each of N-fertilized (FERT) and non N-fertilized mixed-legume (LEG) pastures. For this experiment, each 1.20-ha pasture was split into six, 0.20-ha paddocks for rotational stocking, and the FERT pastures received 90 kg N ha⁻¹ as granular urea on 1 April 2022 and 18 April 2023 (Figure 1).

The DCAFS experiment also had a completely randomized design with three replications of FERT and LEG pastures, along with three non-fertilized pastures not reported in this study. On 17 September 2021 and 19 September 2022, triticale was planted in the FERT and LEG pastures at 112 kg ha⁻¹. About one week later, 13 kg ha⁻¹ red clover cv. Mammoth was seeded in the LEG pastures (24 September 2021 and 28 September 2022). After termination with glyphosate on 2 June 2022 and 15 June 2023, FERT pastures were planted the following day with a monoculture of pearl millet cv. Tifleaf III at 11.2 kg ha⁻¹ and LEG pastures were planted with a mixture of pearl millet

and forage soybean cv. Laredo at 11.2 and 56 kg ha⁻¹, respectively. In FERT pastures, 67 kg N ha⁻¹ was applied as granular urea in the spring on 11 April 2022 and 18 April 2023 and in the summer on 22 June 2022 and 10 July 2023 (Figure 1).

Vegetation Data Collection

In the DPCFS experiment, two paddocks were randomly selected from each pasture to evaluate herbage accumulation. Four grazing exclosures, large enough to center a 0.36 m² quadrat frame, were randomly placed within those paddocks, and herbage was clipped at ground level on two sampling dates to reflect spring and summer herbage accumulation. After the first sampling year, exclosures were relocated by moving within the sampling paddocks. The first sampling occurred on 17 June 2022 and 5 July 2023 (Figure 1). Post harvesting, grazing exclosures were opened and surrounding growth was cut and removed with a string trimmer to reduce the potential for edge effects. Regrowth accumulated during the summer at the DPCFS was clipped on 1 September in 2022 and 2023 (Figure 1).

In the DCAFS experiment, one, 0.36-m² quadrat was clipped at ground level within each of three randomly placed grazing exclosures at the end of the spring grazing period. Herbage components were separated into paper bags by functional groups consisting of perennial grass, legume, weedy grass, and weedy forb, while litter, manure, and standing dead were discarded. The data were collected on 1 June 2022 and 12 June 2023 (Figure 1). The summer sampling in the DCAFS, though, did not occur within grazing exclosures as these pastures were not grazed but were clipped from six random locations within each pasture on 1 September in 2022 and 2023 (Figure 1). Samples were

dried to a constant weight in a forced-air oven at 60°C for at least 72 h, removed from the bag, and weighed on a tray to determine mass of each herbage component.

Animal Management

The following animal management is most pertinent to plant litter collections, as herbage was clipped within grazing exclosures at both locations. In the DPCFS, four crossbred steers of similar weight (275-308 kg hd⁻¹) were turned out onto paddock 1 of each pasture on 5 May 2022 and 4 May 2023. Steers were then rotationally stocked through the remaining paddocks in daily paddock shifts during cycle 1 which ended 11 May 2022 and 10 May 2023. During the second cycle, steers were rotated on 3-d intervals until completing the second cycle on 29 May 2022 and 28 May 2023. In the third cycle, steers were rotated on 6-d intervals on each paddock, which ended on 4 July 2022 and 3 July 2023. During the following cycles, steers were rotated on 3-d intervals or when visual pasture appraisal deemed forage was less than < 5 cm until grazing termination departure, which occurred on 25 August 2022 and 30 June 2023 (112 and 57 grazing days, respectively). After grazing termination, steers were limit-fed and weighed for three consecutive days, and the average weight was used to calculate ADG. During all grazing cycles, steers were sequentially grazed through paddocks 1-6 and given iodized salt blocks ad libitum. One fenceline water tank per pasture was given between every 1st and 2nd, 3rd and 4th, and 5th and 6th paddock and thus was emptied and moved every two cattle rotations.

In the DCAFS, two crossbred steers were turned out onto each pasture on 20 April 2022 and 16 May 2023 and continuously grazed their respective pasture. To maintain a similar grazing intensity across all paddocks, put and take stocking was used

to balance forage height between each experimental unit and was appraised using a drop-disc (data not shown) so number of steers within the pastures varied daily. Steers were removed from experimental pastures on 21 May 2022 and 26 May 2023.

Plant Litter

In the DPCFS, litter cover data were collected in the same two randomly selected paddocks in each pasture at four dates throughout the growing season including on 26 April, 2 June, 7 July, and 12 August in 2022 and 2023 (Figure 1). Twenty-five points were assessed visually in the DPCFS in each selected paddock using the modified step point system outlined by Owensby (1973) to estimate litter cover as compared to bare ground to reflect a total of 42 occurrences ha^{-1} . To do this, 50 point measurements were collected in each paddock in the DCAFS while 25 point measurements were collected in the DPCFS in the same two random paddocks (B and E) within each experimental unit. Litter was counted if the particulate organic matter was at least visible to the naked eye and appeared to be mostly intact, not visually degraded, and appeared functional in reducing rain droplet speed. If the point landed on a plant base, the data were recorded but are not shown, as counts were around 0-2% of occurrences. Cattle manure was not counted in 2022 but was recorded as 'litter' in 2023 as researchers concluded there was little distinction between undigested fiber in manure piles <1 year old and functional litter. Bare ground occurrences were recorded when the sharpened tip of the step point touched bare soil 1) in between plants or litter particles, 2) where cattle pugging occurred, and 3) where rodent, badger, or coyote hole occurred.

Forage Nutritive Value

At both locations, the weedy grass and weedy forb functional groups were combined into the functional group hereafter called ‘weeds’ to obtain enough material to complete nutritive value procedures with. All functional groups were ground in a Wiley mill to 4 mm, subsampled, and ground to 1 mm. After grinding, samples were subsampled again and sent to Ward Laboratories (Kearney, NE) for C/N analysis; estimates were returned on a DM basis. Neutral detergent fiber (NDF) fractionation was completed using the Ankom procedure with F58 filter bags, alpha amylase, and sodium sulfite. *In vitro* organic matter digestibility (IVOMD) was determined for each functional group in 2 runs using methods described by Tilley and Terry (1963). McDougall’s buffer (McDougall, 1948) was added at a rate of 1 g urea L⁻¹ buffer solution, to ensure adequate N availability to rumen microbes (Weiss, 1994). Blank tubes not containing ground sample were used in each *in vitro* run to adjust for contamination from the rumen fluid. Following incubation, samples were filtered through Whatman 541 filter paper, dried at 60°C for 24 hours, then placed in crucibles and heated in a muffle furnace at 600°C for 6 hours. Five hay standards were included to which *in vivo* (total tract) digestibility was known and were used to adjust IVOMD concentrations. Concentrations for C, N, and IVOMD were multiplied by their respective functional group’s mass to determine nutrient yields.

Statistical Analysis

For statistical analyses, we used a mixed model in SAS version 9.4 by system to analyze DCAFS and DPCFS as separate entities. In each analysis, we analyzed each herbage mass component with an ANOVA model that included main effects and their

interactions of pasture type, time of sampling, and year. Time of sampling \times year was included in a repeated statement to signify that these were repeated measures with the subject being the replication within the experimental unit \times pasture type interaction. Least square means and their differences were computed using lsmeans statements followed by corresponding pdiff statements, only including significant main effects or interaction effects.

Results

Weather Conditions

During 2021, precipitation was greater than 2022 and 2023 in August, September, and October by 111-123 mm, 14-24 mm, and 117 mm (October 2023 not shown), respectively (Figure 2). In January, February, April, June, and July, there was 19 mm, 31 mm, 9 mm, 53 mm, and 174 mm greater precipitation in 2023 than in 2022, respectively. In 2022, there was greater precipitation in late summer and fall months than in 2023 including by 12 mm in August, 10 mm in September, 17 mm in October, 12 mm in November, and 27 mm in December in addition to 26 mm in March and 104 mm in May. The months January, February, April, and May were colder on average in 2022 than 2023 (Figure 3). While June and August had relatively similar temperatures between years, July was 2°C warmer in 2022 than 2023. October, November, and December were much colder in 2022 than 2021, with mean differences of 1.5, 2.9, and 6.8 °C.

Double Cropped Annual Forage System

In the DCAFS, mass of forage grasses, legumes, and total forage species all depended on pasture type \times time \times year interactions. Of the weedy species, mass of weedy grasses and total weedy species depended on pasture type \times time and time \times year

interactions while weedy forb mass was not significantly affected across pasture type, time, and year. Total herbage mass depended on a pasture type \times time \times year interaction (Table 1). Forage grass, legume, forage species, and total herbage mass in the DCAFS are displayed in table 16. Forage grass mass did not differ among pasture types in the spring of 2022, the summer of 2022, nor the spring of 2023. However, in the summer of 2023, FERT forage grass was 96% greater than LEG forage grass. Across both pasture types, summer forage grass mass was 711% greater in FERT and 218% greater in LEG than in the spring. In 2022, forage grass mass in the summer was 65% less than in the spring. Legume mass was clearly greater during the summer than the spring, as red clover *nil* across both years. Summer legume mass, which averaged 930 kg ha⁻¹, did not differ between 2022 and 2023. Total forage species mass was not significantly different among pasture types at both sampling times in 2022 nor in the spring of 2023. In the summer of 2023, FERT pasture forage species mass was 69% greater than in LEG pastures. Similarly to forage species mass, total herbage mass was not significantly different among pasture types at both sampling times in 2022 nor in the spring of 2023. The FERT pastures, though, accumulated 68% greater herbage mass than LEG in the summer of 2023. However, herbage mass was not significantly different between sampling times in 2022 in either pasture type. In addition, herbage mass was greater in the summer than in the spring of 2023 in both FERT and LEG pastures with differences of 820% and 322%, respectively.

Table 17 shows weedy grass and weedy species mass in the DCAFS. Weedy grass mass was greatest in the summer sampling time, as weedy grasses in the spring were *nil* while FERT pastures accumulated 2937 kg ha⁻¹ and LEG pastures accumulated 1858 kg

ha⁻¹ in the summer, a 45% difference. Weedy forb mass was *nil* and therefore similar across pasture type, time, and their interaction (data not shown). Because of this, weedy species mass reacted similarly to pasture type and treatment, essentially *nil* in the spring while FERT pastures accumulated 2937 kg ha⁻¹ and LEG pastures 1864 kg ha⁻¹ in summer. Weedy grasses and weedy species were *nil* during the spring sampling time and were significantly greater in the summer of both years (table 18). In the summer, 2022 had 115% greater weedy grass and weedy species mass than in 2023.

In the DCAFS, N concentration in forage grasses depended upon main effects of pasture type, sampling time, and year. However, forage species N concentrations only tended to be dependent on pasture type and year but was dependent on sampling time. Weedy species N concentration was dependent upon pasture type alone in the DCAFS. Also in this system, total herbage N concentrations depended on pasture type and sampling time (Table 3). Tissue N concentrations in the DCAFS are displayed in table 20. The nitrogen concentration in forage grass was 46% greater in FERT than in LEG pastures. Legume N concentration in the LEG pastures contained 19.99 g kg⁻¹ N in their tissues during the summer sampling, improving forage species tissue N to 11.34 g kg⁻¹ in LEG pastures and changing the mean differences of pasture type to only tend towards having different N concentrations. Weedy species tissues had 90% greater N concentrations in FERT than LEG pastures. Meanwhile, total herbage N concentrations were 37% greater within FERT pastures compared to LEG pastures. N concentrations of forage grasses were 67% greater at the spring sampling versus the summer sampling time. Forage species N concentrations were 39% greater in the spring than at the summer sampling time. Weedy species in the summer sampling had tissue N concentrations of

11.22 g kg⁻¹. In addition, total herbage N concentrations in the spring were significantly greater than summer N concentrations, with the spring sampling time having 37% more N in its tissues. Average N concentrations of forage grasses and forage species had greater N concentrations in 2023 than in 2022. In forage grasses, this difference was 24% but in forage species, the difference was only 15% because of high legume N concentrations. Between years, legume and weedy species N concentrations did not differ and total herbage N concentrations only tended to differ.

N yields of forage grasses, forage species, weedy species, and total herbage were all dependent on pasture type × time × year interactions in the DCAFS while legume N yields were dependent on time × year interactions (Table 5). In the DCAFS, N yields of herbage components are displayed in table 21. Nitrogen yields of forage grasses were nearly 10-fold greater in 2023 than in 2022 in both FERT and LEG pasture types. In 2022, spring forage grass N yields were 403% greater in FERT pastures and 501% greater in LEG pastures than in the summer. In 2023 however, FERT pastures had 420% greater summer N yields and LEG pastures had 66% greater summer N yields compared to their respective spring N yields. Forage grass N yields were greater in FERT than LEG pastures in the spring of 2022 and in the summer of 2023, but not in the summer of 2022 nor the spring of 2023. FERT pastures in the spring of 2022 had 83% greater N yields than the summer and 2023 had 235% greater summer N yields than in the spring. Legume N yields did not differ between years but were always greater during the summer sampling time. Weedy species N yields were *nil* in the spring of 2022 and 2023, regardless of pasture type. Weedy species N yields were significantly greater in FERT than LEG pastures during the summer sampling time of both years, with 206% greater N

yields in the summer 2022 and 185% greater N yields in the summer of 2023. Total herbage N yields were similar across sampling times in 2022 but were 509% greater in FERT and 173% greater in LEG during the summer than the spring of 2023. Additionally, total herbage N yields were greater in FERT than the LEG pasture type in 2022, with 83% greater N yields in the spring and 78% greater N yields in the summer. In 2023, spring herbage N yields did not differ between FERT and LEG pastures, but summer N yields were 137% greater in FERT pastures.

In the DCAFS, NDF concentrations of forage grasses, forage species, legumes, and total herbage were dependent on sampling time \times year interactions. Weedy species and forage species depended on a pasture type \times time interaction while total herbage had a tendency towards this interaction (Table 7). In the DCAFS, NDF concentrations are displayed by year in table 26. NDF concentrations of forage grass at the spring sampling time were 33.3 g kg⁻¹ less in 2022 than 2023 but the summer sampling had 23.9 g kg⁻¹ greater NDF in 2022 than 2023. In 2022, there was no difference in forage grass NDF between sampling times but in 2023, the summer sampling was 71.5 g kg⁻¹ greater than NDF of the spring forage grass. Forage species NDF concentrations were 33.0 g kg⁻¹ less in 2023 during spring but were 40.1 g kg⁻¹ less in 2022 than 2023 during the summer. While forage species NDF was not different between sampling times in 2022, summer NDF concentrations were 70.7 g kg⁻¹ greater than the spring of 2023. Weedy species NDF concentrations did not differ between years at the summer sampling date. Total herbage NDF concentrations were 31.8 g kg⁻¹ less in 2023 than in 2022 at the spring sampling time but during the summer sampling time, NDF concentrations were 24.8 g kg⁻¹ greater in 2023.

In the DCAFS, NDF concentrations within each pasture type and sampling time are shown in table 27. NDF concentrations of forage grass did not differ between pasture types in spring nor summer. Averaged across pasture types, summer NDF concentrations of forage grass were 42.9 g kg⁻¹ greater than spring NDF concentrations. Forage species NDF concentrations did not differ between pasture types in the spring, but FERT had 35.7 g kg⁻¹ greater NDF than LEG during the summer sampling time. Both LEG pasture types had similar NDF concentrations in forage species at spring and summer sampling times but FERT pastures had 47.6 g kg⁻¹ greater NDF during the summer compared to the spring sampling time. Weedy species had an 18.5 g kg⁻¹ greater NDF concentration in LEG than FERT pastures during the summer sampling time. Total herbage NDF concentrations did not differ between pasture type in the spring but in the summer, LEG was 16.6 g kg⁻¹ less than FERT. FERT had 46 g kg⁻¹ less herbage NDF concentrations in spring than summer, but no difference occurred among sampling times in LEG while LEG pastures had a tendency to have greater NDF in the summer than the spring.

In the DCAFS, IVOMD concentrations of forage grasses, forage species, and total herbage were dependent on pasture type × sampling time × year interactions. Legume IVOMD concentrations were sampling time dependent and weedy species IVOMD concentrations were dependent on sampling time × year interactions in the DCAFS (Table 9). In the DCAFS, IVOMD concentrations of herbage components are listed in table 30. Spring and summer forage grass IVOMD concentrations did not differ between pasture types in 2022, but in 2023, forage grass IVOMD concentration was 47.1 g kg⁻¹ less in LEG than FERT pastures in spring and 52.2 g kg⁻¹ greater in LEG than FERT pastures in summer. In 2022, FERT and LEG pastures had 75.2 g kg⁻¹ and 91.7 g kg⁻¹

greater forage grass IVOMD concentrations in summer than spring,. In 2023, forage grasses had 107.6 g kg^{-1} less IVOMD in summer than spring in FERT pastures but similar IVOMD in spring and summer in LEG pastures. Forage species IVOMD was similar between FERT and LEG pastures in the spring and summer of both years. Forage species IVOMD, meanwhile, was 68.6 g kg^{-1} greater in summer than spring in 2022 averaged across pasture types. In FERT pastures, IVOMD concentrations of forage species were 107.6 g kg^{-1} less in summer than spring in 2023 while LEG pastures did not differ. In 2022, weedy species IVOMD concentration was not different in summer but in 2023, weedy species had 78.8 g kg^{-1} greater IVOMD in LEG than FERT. Total herbage IVOMD was similar between pasture types in spring and summer in 2022 but was 47.1 g kg^{-1} greater and 42.4 g kg^{-1} less in FERT than LEG during spring and summer sampling times, respectively, in 2023. In 2022, herbage IVOMD concentrations were 37.5 and 42.4 g kg^{-1} greater in summer than spring in FERT and LEG pastures, respectively. In 2023, herbage IVOMD was similar across sampling times in LEG pastures but 112.9 g kg^{-1} less in summer than spring in FERT pastures.

In the DCAFS, IVOMD yields of forage grasses, forage species, and total herbage were dependent on pasture type \times sampling time \times year interactions. Weedy species IVOMD yields at this location tended towards pasture type \times sampling time interactions but were only dependent on pasture type main effects with a sampling time \times year interaction. Legume IVOMD yields in the DCAFS were only dependent on time main effects (Table 11). In the DCAFS, IVOMD yields are shown in table 31. Forage grass IVOMD yields did not differ by pasture type during the spring or summer in 2022 or in the spring of 2023. However, during the summer of 2023, forage grass IVOMD yield was

44% less in LEG than FERT pastures. In 2022, FERT had 158% greater forage grass IVOMD yield in the spring compared to summer and LEG pastures had 145% greater forage grass IVOMD yield in spring than summer. In 2023, FERT and LEG pastures had 583% and 215% greater forage grass IVOMD yield in the summer than the spring. Like forage grass, forage species IVOMD yield only differed by pasture type in the summer of 2023, with LEG having 36% less than FERT. In 2022, forage species IVOMD yield was 61% less in summer than spring in FERT pastures. In 2023, forage species IVOMD yield were 582% greater in FERT and 262% greater in LEG during the summer compared to spring. Weedy species IVOMD yield was 55% greater in FERT than LEG pastures in the summer of 2022 but not significantly different in the summer of 2023. Total herbage IVOMD yield did not differ across pasture type or sampling time in 2022 but in 2023, herbage IVOMD yield was 56% greater in FERT than LEG in summer. In 2023, herbage IVOMD yields were 668% and 309% greater during the summer than spring in FERT and LEG pastures, respectively.

In the DCAFS, bare ground and litter counts were affected by sampling time \times year interactions. At this location, bare ground tended toward pasture type main effects but no tendencies were observed in litter counts (Table 13). In the DCAFS, basal cover is shown as bare ground and litter cover in figure 4. Bare ground exposure in 2022 began with 35.7% in June and was similar until September, where bare ground was reduced to 19.6%. During this year, litter cover was consistently greater than bare ground cover across the season. Beginning in June with 58.0%, litter cover improved to 66.0% in August and 74.0% by September. In 2023, bare ground exposure in June began with 37.3% bare ground in June and increased to 49.7% in and increased by August. During

September, bare ground surpassed litter cover 11.7% units more than litter cover, increasing bare ground from June and July but decreased litter cover from these dates across the growing season.

Diverse Perennial Circular Forage System

In the DPCFS, mass of forage species components including forage grasses and total forage species both depended on time \times year interactions while legumes depended on pasture type alone. Among weedy species, mass of weedy grasses and total weedy species depended on time \times year interactions while forb mass was not significantly affected by pasture type, time, or year. Total herbage in the DPCFS also depended on time \times year interactions (Table 2). In the DPCFS, herbage component mass is displayed in table 19. Forage grass was greater during the spring sampling time than the summer sampling time across both years. This was most pronounced in the spring of 2022, when forage grass was 7179 kg ha⁻¹ greater than in the summer sampling date whereas the spring of 2023 was only 1318 kg ha⁻¹ greater than in the summer sampling date. In 2022, forage grass mass was 41% greater during the spring sampling date than in 2023 while the summer of 2022 accumulated 402% greater forage grass mass. Consequently, these two years had similar forage grass mass in 2022 and 2023, averaged across sampling dates. Forage species mass reacted similarly to forage grass mass, as legumes made up a small component of the legume treatment across sampling times and years (204 kg ha⁻¹). In the spring of 2022, forage species mass was 40% greater than in 2023 and was 353% greater in the summer of 2022 than the summer of 2023. Across years, spring forage species mass was greater than summer which again, was more pronounced in 2022 than in 2023 with mean differences of 7201 kg ha⁻¹ and 1408 kg ha⁻¹, respectively.

DPCFS had significant weedy grass mass only during the summer of 2023, whereas spring sampling times and summer of 2022 had *nil* weedy grass accumulation. Weedy species mass was similar to weedy grass mass during each year and sampling time, and was significant only during the summer of 2023. Like forage species, total herbage mass was greatest during spring sampling compared to summer sampling times, where 2022 had a mean difference of 7219 kg ha⁻¹ and 2023 had a mean difference of 1222 kg ha⁻¹. In 2022, spring herbage mass was 40% greater than in spring of 2023 but during the summer, herbage mass was 360% greater in 2023 than in 2022.

In the DPCFS, forage grass N concentration was dependent on pasture type × sampling time and sampling time × year effects while legume N concentration depended on sampling time alone. Like forage grass, forage species N concentrations in this study were also dependent on pasture type × sampling time and sampling time × year interactions. Total herbage N concentrations were dependent on sampling time × year interactions (Table 4). N concentrations of forage grasses, forage species, and total herbage followed similar trends across years and sampling times (Table 22). Forage grasses were 44% greater in the spring of 2023 compared to 2022, but in the summer of 2022, N concentrations were 47% greater than in the summer of 2023. Within each year, N concentrations of forage grasses were greater in the summer by 137% in 2022 but only 12% in 2023. Forage species had a 43% greater tissue N concentration in the spring of 2023 compared to the spring of 2022 but had a 30% less N concentration in the summer of 2023 compared to 2022. Between sampling times, forage species had a 135% greater N concentration during the summer than the spring of 2022 but only 11% greater tissue N during the summer than the spring of 2023. Additionally, total herbage N concentration

was 43% greater in the spring of 2023 compared to the spring of 2022 while the summer of 2023 was 30% less than the N concentration in the summer of 2022. During the summer of 2022, herbage N concentration was 124% greater compared to the spring but the summer of 2023 had only a 10% greater N concentration than the spring of 2023.

Forage grass and forage species N concentrations in FERT and LEG pastures were greater in the summer than in the spring (Table 23). Forage grass N concentrations were 23% greater in FERT than LEG pastures during the spring sampling date, but summer N concentrations of FERT pastures were only 5% less. Nitrogen concentrations in forage grasses were 51% greater in the summer in FERT and 77% greater in summer in the LEG pastures compared to their respective spring sampling concentrations. Forage species N concentrations were 19% greater in FERT compared to LEG pastures during spring sampling but were only 8% greater during the summer sampling time. While FERT forage species had 51% greater N concentrations during the summer than the spring, LEG forage species had 67% greater N concentrations during the summer. Unlike forage grass and forage species, legume N concentrations were 20% greater in the spring than in the summer sampling date (Table 23).

In the DPCFS, N yields of forage grasses and forage species were dependent on pasture type main effect and sampling time \times year interactions while weedy species were only dependent on sampling time \times year. Total herbage N yields in the DPCFS were dependent on pasture type \times time and time \times year interactions (Table 6). N yields of forage grass, forage species, weedy species, and total herbage did not differ between years at each spring sampling time, however, these functional groups had 247%, 220%, 748%, and 228% greater N yields during the summer of 2023 compared to the summer of

2022, respectively (Table 24). Forage grass N yields were 295% greater in the spring than summer of 2022 but were only 16% greater in the spring than the summer in 2023.

Forage species N yields were 272% greater in the spring of 2022 but in 2023, spring N yields were 18% greater than during the summer sampling time. Weedy species N yields did not differ across sampling times during 2022, but they were significantly greater in the summer of 2023 than the spring. However, the mean difference was only 3.2 kg N ha⁻¹. Of the total herbage N yields, 2022 was 270% greater during the spring than the summer while 2023 had 15% greater N yields during the spring than the summer sampling time.

Forage grass, forage species, and total herbage N yields were greater in the spring than the summer, and in FERT than in LEG pastures (Table 25). Forage grass had 48% greater N yields in FERT than LEG pastures during the spring while summer N yields were 41% greater in FERT than LEG pastures. FERT pastures had 82% greater forage grass N yields during the spring than summer while LEG pastures had 73% greater forage grass N yields during the spring. Forage species in FERT pastures had 38% greater N yields than LEG pastures during the spring whereas FERT pastures had 32% greater N yields than LEG in the summer. FERT pastures had 82% and LEG pastures had 75% greater forage species N yields in the spring compared to summer. Total herbage N yields were 38% greater in the spring sampling time and 30% greater in the summer sampling time in FERT pastures compared to LEG pastures. FERT pastures had 79% greater and LEG pastures had 69% greater herbage N yields in spring compared to summer.

In the DPCFS, NDF concentrations of forage grasses, forage species, and total herbage depended on sampling time × year interactions while weedy species were not

affected by any treatment applied (Table 8). In the DPCFS, NDF concentrations are shown by year and sampling time in table 28. Forage grass NDF concentration was 42.5 g kg⁻¹ less in the spring of 2023 compared to the spring of 2022 but 120 g kg⁻¹ less in the summer of 2022 compared to the summer of 2023. Forage grass NDF concentration was 150 g kg⁻¹ less in spring than in summer in 2022, but in 2023, it remained the same across sampling times. Forage species had 47.4 g kg⁻¹ less NDF in 2023 than in 2022 at the spring sampling time while having 131.3 g kg⁻¹ greater NDF in 2023 than 2022 at the summer sampling time. In 2022, forage species had 159.3 g kg⁻¹ less NDF in the summer sampling date compared to the spring while in 2023, there was a tendency for the summer sampling NDF concentration to be higher. Total herbage NDF concentration followed a similar trend to forage grass and forage species, having 48.1 g kg⁻¹ less NDF in 2023 than 2022 at the spring sampling time and 122.6 g kg⁻¹ greater NDF in 2023 than 2022 at the summer sampling time. Herbage NDF was 161.8 g kg⁻¹ less in the summer than the spring of 2022 but in 2023, there was no difference in NDF concentrations between sampling times.

In the DPCFS, NDF concentrations of herbage components are listed by year and sampling time in table 29. Forage grass NDF concentrations tended to be greater in LEG pastures compared to FERT pastures in the spring while there was no difference in NDF concentrations between FERT and LEG pastures in the summer. In FERT pastures, NDF concentrations were 62.4 g kg⁻¹ less in the summer than the spring and LEG pastures had 76.5 g kg⁻¹ less NDF in the summer than in the spring. Forage species, weedy species, and total herbage NDF concentrations did not differ between pasture type at either sampling time, and averaged together, forage species had 69.9 g kg⁻¹ less NDF in the

summer, weedy species and legumes had no difference, and total herbage had 76.5 g kg⁻¹ less NDF in the summer than in the spring.

In the DPCFS, IVOMD concentrations of forage grasses and forage species depended on a pasture type × year interaction but total herbage only tended toward this interaction. Instead, total herbage IVOMD concentrations were dependent on sampling time and year main effects, while weedy species and legumes were not affected by any variable in the DPCFS (Table 10). In the DPCFS, IVOMD concentrations of forage grasses, forage species, weedy species, and total herbage were not different between years at the spring sampling time, and weedy species IVOMD concentrations did not differ within years across sampling times (Table 32). During the summer, IVOMD concentrations of forage grasses were 62.5 g kg⁻¹ less in 2023 than 2022. In 2022, summer IVOMD concentrations were 98 g kg⁻¹ greater than the spring, and in 2023, summer had 49.6 g kg⁻¹ greater IVOMD than the spring. Forage species had 63.5 g kg⁻¹ greater IVOMD in 2022 compared to 2023 at the summer sampling time. Total herbage IVOMD was 59.4 g kg⁻¹ less in 2022 than in 2023 at the summer sampling. Total herbage had 98.6 g kg⁻¹ and 57.3 g kg⁻¹ greater IVOMD in summer than the spring in 2022 and 2023, respectively.

In the DPCFS, forage grasses, forage species, and total herbage IVOMD yields were all dependent on sampling time × year interactions and tended toward having pasture type main effects. In this system, legume and weedy species IVOMD yields were not affected by time or year (Table 12). In the DPCFS, IVOMD yields of herbage components by year and sampling time are shown in table 33. Forage grass IVOMD yield was 31% less in spring of 2023 than 2022 but in the summer, 2023 IVOMD yield was

351% greater than in 2022. During both years, spring IVOMD yield was greater than summer yield, with 677% more in 2022 and 19% more in 2023. Forage species also had 31% less IVOMD yield in 2023 than 2022 during the spring sampling, but in the summer sampling time, there was 309% more IVOMD in 2023. In 2022, forage species IVOMD yield was 86% less in the summer compared to spring, but in 2023, forage species IVOMD yield was only 17% less in summer. Weedy species IVOMD yield did not differ significantly between years in spring, but it showed a tendency to be greater in 2023 than 2022 in summer and in summer than spring in 2023. Herbage IVOMD yield was 31% less in 2023 compared to 2022 in spring but was 316% greater in 2023 than 2022 in summer. Total herbage IVOMD yield in spring was 588% greater than during summer in 2022 but only 14% in 2023.

In the DPCFS, bare ground and litter counts were observed to have sampling time \times year interactions with no pasture time main effects or tendencies (Table 14). In the DPCFS, basal cover is shown as bare ground and litter cover in figure 5. Bare ground exposure was at similarly low percentages across sampling times and years. Litter cover, on the other hand, increased from a low of 81.3% in June of 2022 to 90.7% by July, remaining similar for the rest of the sampling times. In 2023, litter cover was similar across all sampling times, averaging 90.8% .

In the DPCFS, steer initial BW, final BW, ADG, and total gains were dependent on year main effects alone. A tendency toward a pasture type \times year interaction was observed for initial BW (Table 15). In the DPCFS, BW began at 277 ± 0 kg hd^{-1} and ended at 365 ± 3 kg hd^{-1} in 2022 and in 2023, steers began at 307 ± 0 kg hd^{-1} and ended at 373 ± 3 kg hd^{-1} in 2023. In 2022, steers gained 88 ± 3 kg hd^{-1} over the 112-d grazing

season with ADG of 0.79 ± 0.04 kg $\text{hd}^{-1} \text{d}^{-1}$. In 2023, steers gained 66 ± 3 kg hd^{-1} in only 57 d with ADG of 1.11 ± 0.04 kg $\text{hd}^{-1} \text{d}^{-1}$.

Discussion

Double Crop Annual Forage System

In the DCAFS, N fertilization in the FERT pastures had no impact on triticale herbage accumulation in the spring compared to unfertilized triticale in the LEG pastures. In the spring LEG pastures, red clover was not present in enough quantities to improve total herbage mass. Other studies have shown that red clover may struggle to compete and accumulate biomass in spring (Baraibar et al., 2018), yet probably not as poorly as in our study. Factors that may have contributed to poor red clover performance include the seeding method, fall planting instead of frost-seeding (Blaser et al., 2006), or the planting depth. In addition to very little red clover present, there were nearly no weeds present during spring sampling times, and those present were summer annual grass seedlings that were just emerging and had amounted to no biomass. Thus, herbage accumulation across the spring was essentially 100% triticale and equal across the FERT and LEG pasture types.

In the DCAFS in the dry summer of 2022, forage soybean did not accumulate enough mass to improve forage species mass in the LEG compared to FERT pastures. Forage grass, forage species, and total herbage mass components also were similar across pasture types. In the wetter summer of 2023, however, the high precipitation improved pearl millet accumulation in FERT by nearly double compared to the LEG pastures. Warm-season annual forage grasses are commonly known to increase mass under N fertilization, and they have high N use efficiency under wetter conditions (Sawargaonkar

et al., 2013). In LEG pastures, forage soybean did not improve forage species accumulation enough to compensate for this gain by N fertilization in the wet summer. Others have observed forage soybean to have even lower productivity and contribute a smaller proportion of biomass (<4%) (Mercier et al., 2021) than what it did in our study (12-15%) when grown in a mixture with warm-season annual grasses. In a comparison of forage soybean intercropped with a relatively thin stand of forage sorghum compared to our study, Redfearn et al. (1999) saw a 36% reduction in legume mass. This clearly explains why our forage soybean mass was so low. Weedy grass accumulation was 1083 kg ha⁻¹ greater in FERT than LEG pastures, a likely response to increasing soil N availability. Additionally, weedy grass accumulation was more than twice that of the wetter summer of 2023 during the drier summer of 2022 when forage mass was low, indicating their relative contribution to total herbage mass was greater during 2022.

Nitrogen fertilization has previously been shown to increase tissue N concentrations in cereal grain cover crops (Balkcom et al., 2018), summer annual forages (Heitman et al., 2017), and weeds (Blackshaw et al., 2002) and did so in our study at both sampling times. In forage species averaged across years and sampling times, the high N concentrations in legume tissues nearly made up for the effects of N fertilization on N concentrations. Triticale N concentrations were greater than pearl millet N concentrations, also making N concentrations of spring forage species greater than in the summer. Year also seemed to affect N concentrations of forage grasses, by improving them in the year with the wet summer.

Nitrogen yields in forage grasses in the DCAFS were much greater in FERT than LEG pastures in the spring of 2022, which had more moisture than the spring of 2023.

During the summer of 2023, it was evident that the summer rainfall dramatically increased N yields in FERT pastures to a greater degree than in LEG pastures, as forage grasses had more than three-fold greater N yields in FERT than LEG pastures and forage species, weedy species, and total herbage had more than double the N yields in FERT than LEG pastures. In the summer of 2022, smaller differences were detected in N yields but only between weedy species and total herbage. These data come as no surprise, as irrigation has been shown to improve N uptake and use efficiency in other species, including sorghums (Sigua et al., 2018).

In the DCAFS, triticale NDF concentrations were lower in the drier spring of 2023 than the spring of 2022, but pearl millet had greater NDF in the wetter summer of 2023 than the summer of 2022. This could have resulted from the difference in precipitation, as increasing irrigation has been shown to increase NDF concentrations in sorghum species harvested at the same stage (Carmi et al., 2006). Contrasting pasture types, legumes significantly decreased forage species NDF concentrations in LEG pastures compared to forage grass NDF. Redfearn et al. (1999) showed that forage soybean NDF was highly dependent on the leaf mass compared to stem mass, as leaf NDF concentrations were 339 g kg^{-1} while stems were $645\text{-}681 \text{ g kg}^{-1}$ and saw that intercropping significantly decreased stem NDF. Weedy species had similar NDF concentrations to pearl millet, so total herbage NDF concentrations were not greatly impacted by the different proportions of weedy species in the two summers. LEG pastures also had lower NDF concentrations than FERT pastures, despite having slightly greater weedy species NDF concentrations.

Forage grass IVOMD concentrations and yields did not differ between pasture types during 2022, the year with a wet spring and dry summer, but triticale, the spring forage grass component, had lower IVOMD concentrations than pearl millet, the summer forage grass component, in both pasture types that year. However, since triticale had much greater mass than pearl millet that year, IVOMD yields of forage grasses were greater in FERT pastures and were nearly greater in LEG pastures in spring than summer. Forage soybean did not change the IVOMD concentrations of forage species in LEG pastures during the dry summer nor did the total herbage IVOMD concentrations change after accounting for weeds, and IVOMD yields were similar between both pasture types at both sampling times. Ultimately, in the year with the wet spring and dry summer, carrying capacities of the total herbage would likely be similar during spring and summer across both pasture types, indicating that fertilization was probably not worth the cost. A similar argument could be made for the inclusion of the legume seed because it only accounted for a small portion of the IVOMD yields in the herbage.

In the year with the dry spring, 2023, the triticale component had greater IVOMD concentrations in FERT than LEG pastures and visually appeared to be more tillered and less mature; however, IVOMD yields did not differ between pasture types. There has been extensive research on the effects of N fertilization on small grain crops, and this effect has been documented in wheat, where increasing N fertilization increases total tiller density by promoting underground buds to break dormancy and increase the proportion of infertile tillers (Zhang et al., 2020). The bud break and increased tiller density is likely a direct effect of fertilization creating cytokinin hormone responses within lateral buds (Wang and Below, 1996). During dry conditions, this effect may have

been especially apparent because the plant allocated what little resources it had from apical meristem dominance in tillers to lateral meristem growth, exhausting its resources and setting back tiller maturity. Therefore during dry conditions, spring N applications to cereal grain forages has the potential to increase nutritive value concentrations with the tradeoff of reduced or delayed productivity.

In the DCAFS, differences between years for litter cover was a function of precipitation after triticale termination, as plant litter is known to decay at faster rates under exposure to increasing relative moisture (Hood, 2001). In the first year, litter cover accumulated after July and since there was a low amount of precipitation that summer, bare ground cover remained constant. In 2023, soil litter cover declined between July and September, even though there was more litter remaining post grazing of triticale in spring (data not shown). By September of that year, bare ground had exceeded litter cover.

Diverse Perennial Circular Forage System

In the DPCFS, there were no differences in mass of herbage components between pasture types, indicating that in smooth brome grass pastures, N fertilization does not improve herbage mass compared to perennial mixed grass-legume pastures. Indeed, in previous years, the mixed grass-legume pastures have been shown to have greater smooth brome grass production than the N fertilized pastures. This “transgressive overyielding” effect has also been observed in stands with perennial legumes that have only been established. Transgressive overyielding could potentially be greater in long term mixed grass-legume pastures under grazing such as in the DPCFS, but more research should be done before conclusions can be made comparing grazed and hayed systems.

In the DPCFS, the wetter spring and drier summer in 2022 caused greater differences in mass of herbage components between sampling times than was seen in 2023 which had a dry spring and wet summer. In 2022, smooth brome grass accumulated 8054 kg ha⁻¹ of dry matter in the spring but only 875 kg ha⁻¹ during the summer. In 2023, though, smooth brome grass accumulated 5713 kg ha⁻¹ of dry matter in the spring and 4395 kg ha⁻¹ in the summer. Forage species and total herbage mass followed the same trend as the forage grass component since legumes and weedy species were only a small portion of herbage in both years.

Nitrogen yields of smooth brome grass in the DPCFS were much greater in the summer than spring in 2022, with a difference of 18.7 kg N ha⁻¹ versus a difference of 2.38 kg N ha⁻¹ in 2023. Even though there were no differences in forage grass and forage species mass between pasture types, FERT had greater N yields in forage grass and forage species mass than LEG at both sampling times with the greatest of these differences occurred during the spring sampling. Among years, smooth brome grass, forage species, and total herbage N yields differed between the summers, as 2023 produced more than triple the N yields of 2022. Among pasture types, however, the greatest N yields and variation between N yields occurred within the spring sampling times, in which differences were around 40 kg N ha⁻¹ greater in FERT than LEG pastures but around 20 kg N ha⁻¹ in the summer. These data indicate that spring applied N fertilizer is more impactful on N uptake during the spring because by summer, the N fertilizer has been assimilated, leached out of the soil, denitrified, and volatilized, or conditions are simply not conducive to growth and subsequent N uptake (Follett and Delgado, 2002).

In the DPCFS, smooth brome grass NDF concentrations, being 150.7 g kg^{-1} greater during the spring than summer of 2022, indicates the summer growth was very immature from the lack of precipitation, and this can be validated with the low summer dry matter accumulation that year. In the next year, spring and summer NDF concentrations of smooth brome grass were similar because of a large quantity of rainfall in the summer. Averaged across years, smooth brome grass had lower NDF concentrations during the summer compared to spring, which was expected as clipping makes subsequent growth young and summer conditions grow cool season perennial grasses slowly. Forage species and herbage NDF concentrations were not greatly impacted by legume and weedy species, as they accounted for a small portion relative to smooth brome grass.

IVOMD concentrations of summer regrowth of smooth brome grass were always greater than springtime accumulations. However, the amount of high-quality weedy species during the summer months made total herbage closer in IVOMD yields. During the wet summer, when the herbage had a chance to accumulate more forage, IVOMD concentrations were less but IVOMD yields were much higher compared to the dry summer. Because of the dry spring in 2023, IVOMD yields of smooth brome grass pastures were lower than during the spring of 2022.

System Comparison

Herbage mass in the DCAFS was more evenly distributed compared to the DPCFS during the year with low spring moisture and high summer moisture. However, summer weeds accounted for a greater proportion of herbage mass in summer than in spring in the DCAFS and reduced total herbage IVOMD concentrations whereas weeds

only accounted for a small portion of the herbage mass in the DPCFS during the summer of 2022. In 2023, the DPCFS herbage mass and IVOMD yields were more evenly distributed across sampling times compared to the DCAFS, especially because pearl millet was so productive during that year.

Herbage accumulation and nutritive value in the DCAFS seemed to be largely driven by the presence of precipitation, phenomena also noted in a 5 year study evaluating grazing of a double-cropped annual forage system in North Dakota (Sedivec et al., 2011). Additionally, wetter years would allow more grazing days than drier years in an annual system compared to a perennial system. This was seen in a 5 year study comparing the average of three wet seasons where cereal rye-annual ryegrass mixtures had 9% more grazing days ha^{-1} than tall fescue pastures but during a dry year when tall fescue was fully established, grazing days were similar between systems (Islam et al., 2011). Herbage in the DPCFS generally had its greatest nutritive value for summer regrowth. However, DCAFS nutritive values varied between years and pasture types to a larger extent than the DPCFS. In a hypothetical scenario where precipitation was plentiful at both sampling times, our data suggests herbage IVOMD and NDF concentrations may be numerically closer between samplings times in the DCAFS than the DPCFS; the same can be said if precipitation was low at both sampling times. This indicates that the DCAFS herbage might have more evenly distributed nutritive value than the DPCFS under optimum precipitation conditions, as cool season perennial pastures like smooth bromegrass (Lauriault et al., 2005) and tall fescue (Asay et al., 2002) see forage growth reductions in the summer, regardless of irrigation management.

A previous 3-year study in this DPCFS showed how differences in herbage mass and nutritive values resulted in differences for animal performance across the season. When legumes were around 20% of the annual forage mass, they increased forage mass further into the summer. This resulted in significantly greater ADG during the second half of the grazing season, from June to October, compared to N fertilized pastures (Hillhouse et al., 2021). By the time of our study, the legume component had diminished low enough where there was no longer a difference in herbage IVOMD yields, and likely not ADG, between pasture types during the spring sampling times in both years nor at the summer sampling time of 2022. IVOMD yields of herbage differed between pasture types in the summer of 2023, but steers had been removed before this additional growth would have been grazed.

It comes as no surprise that we had greater litter cover in smooth brome grass pastures compared to annual pastures. Mapfumo et al. (2002) saw the same relationship in their study as litter mass was always much greater in smooth brome grass pastures compared to triticale pastures. However, our DCAFS was likely a better comparison to DPCFS because Mapfumo et al. (2002) followed triticale with a fallow period rather than a warm season forage and smooth brome grass does not have a fallow period. Additionally, DPCFS litter cover was more resistant to change through the seasons compared to the DCAFS which may allow it to sustain greater labile carbon stocks, lose fewer nutrients to runoff (Avalos et al., 2009), and reduce raindrop speeds which allows its soil to maintain lower bulk density (Dao, 1996). However, litter in smooth brome grass pastures is positively correlated with soil moisture but productivity can be increased via litter removal because of improved tillering (Deutsch et al., 2010). Therefore, grazing

probably increases productivity of smooth brome grass pastures by removing some biomass that would potentially become residue and opening the residue layer via treading and improve tillering.

In central Oklahoma, a comparison between grazing novel endophyte tall fescue pastures versus a cereal rye-annual ryegrass mixture found that in the short term (5 years), the annual system was more profitable but if costs were amortized over 12 years, these two systems became similar in profitability, at \$279 ha⁻¹ (Islam et al., 2011). In northern Arkansas, novel endophyte tall fescue grazed over three seasons had greater net returns than a wheat-cereal rye mixture but similar to or less profitable returns than annual ryegrass pastures, depending on year, moisture, and subsequent grazing period length (Beck et al., 2008). However, in eastern Nebraska, annual ryegrass is likely not a good option for grazing because the cold and dry winter climate creates slow and stunted spring growth, as was seen in central Missouri (Kallenbach et al., 2006).

Conclusion

Grazed smooth brome grass pastures maintained greater litter cover and were more resistant to fluctuations in soil cover across the growing season whereas litter cover of double-cropped annual forage systems differed depending on growing season precipitation. In smooth brome grass pastures, herbage mass is usually greater in the spring than summer. However, when precipitation is low in the spring but high in the summer, smooth brome grass may accumulate more equal herbage mass and nutritive value across the growing season. A double-cropped annual forage system, though, is not likely to have equal forage accumulation in spring and summer. This is because N fertilized summer annual forages, such as pearl millet, are capable of accumulating

greater nutritive value growth compared to triticale, particularly when summer precipitation is high. When summer precipitation is low, pearl millet can become weedy with low forage. However, in smooth brome grass pastures, weeds remained suppressed and can have greater digestibility and N concentrations. Therefore, summer annual pastures can provide highly nutritious supplemental forage during summers that are not excessively dry.

In smooth brome grass pastures with 13-year-old remnant mixed-legumes compared to long term N fertilized pastures, we observed relatively little benefit to N fertilization besides increasing N in tissues. In double cropped annual forage systems, legumes did produce enough mass to improve herbage mass or nutritive value to compete with N fertilization. Therefore, N fertilization is needed to improve annual pasture productivity, but not perennial pastures if they have been mixed with legumes in the last 13 years.

Literature cited

- Asay, K.H., K.B. Jensen, B.L. Waldron, G. Han, D.A. Johnson, et al. 2002. Forage Quality of Tall Fescue across an Irrigation Gradient. *Agron. J.* 94(6): 1337–1343. doi: 10.2134/agronj2002.1337.
- Avalos, J.M.M., P.S. Fouz, E.V. Vázquez, A.P. González, and I. Bertol. 2009. Crop Residue Effects on Organic Carbon, Nitrogen, and Phosphorus Concentrations and Loads in Runoff Water. *Commun. Soil Sci. Plant Anal.* 40(1–6): 200–213. doi: 10.1080/00103620802625542.

- Balkcom, K.S., L.M. Duzy, F.J. Arriaga, D.P. Delaney, and D.B. Watts. 2018. Fertilizer Management for a Rye Cover Crop to Enhance Biomass Production. *Agron. J.* 110(4): 1233–1242. doi: 10.2134/agronj2017.08.0505.
- Baraibar, B., M.C. Hunter, M.E. Schipanski, A. Hamilton, and D.A. Mortensen. 2018. Weed Suppression in Cover Crop Monocultures and Mixtures. *Weed Sci.* 66(1): 121–133. doi: 10.1017/wsc.2017.59.
- Beck, P.A., S.A. Gunter, K.S. Lusby, C.P. West, K.B. Watkins, et al. 2008. Animal performance and economic comparison of novel and toxic endophyte tall fescues to cool-season annuals¹. *J. Anim. Sci.* 86(8): 2043–2055. doi: 10.2527/jas.2007-0522.
- Blackshaw, R.E., G. Semach, and H.H. Janzen. 2002. Fertilizer application method affects nitrogen uptake in weeds and wheat. *Weed Sci.* 50(5): 634–641. doi: 10.1614/0043-1745(2002)050[0634:FAMANU]2.0.CO;2.
- Blaser, B.C., L.R. Gibson, J.W. Singer, and J.-L. Jannink. 2006. Optimizing Seeding Rates for Winter Cereal Grains and Frost-Seeded Red Clover Intercrops. *Agron. J.* 98(4): 1041–1049. doi: 10.2134/agronj2005.0340.
- Buxton, D.R., I.C. Anderson, and A. Hallam. 1999. Performance of Sweet and Forage Sorghum Grown Continuously, Double-Cropped with Winter Rye, or in Rotation with Soybean and Maize. *Agron. J.* 91(1): 93–101. doi: 10.2134/agronj1999.00021962009100010015x.

- Carmi, A., Y. Aharoni, M. Edelstein, N. Umiel, A. Hagiladi, et al. 2006. Effects of irrigation and plant density on yield, composition and *in vitro* digestibility of a new forage sorghum variety, Tal, at two maturity stages. *Anim. Feed Sci. Technol.* 131(1): 121–133. doi: 10.1016/j.anifeedsci.2006.02.005.
- Dao, T.H. 1996. Tillage System and Crop Residue Effects on Surface Compaction of a Paleustoll. *Agron. J.* 88(2): 141–148. doi: 10.2134/agronj1996.00021962008800020005x.
- Deutsch, E.S., E.W. Bork, and W.D. Willms. 2010. Soil moisture and plant growth responses to litter and defoliation impacts in Parkland grasslands. *Agric. Ecosyst. Environ.* 135(1): 1–9. doi: 10.1016/j.agee.2009.08.002.
- Egan, M., N. Galvin, and D. Hennessy. 2018. Incorporating white clover (*Trifolium repens* L.) into perennial ryegrass (*Lolium perenne* L.) swards receiving varying levels of nitrogen fertilizer: Effects on milk and herbage production. *J. Dairy Sci.* 101(4): 3412–3427. doi: 10.3168/jds.2017-13233.
- Floate, M.J.S. 1981. Effects of Grazing by Large Herbivores on Nitrogen Cycling in Agricultural Ecosystems. *Ecol. Bull.* (33): 585–601.
- Follett, R.F., and J.A. Delgado. 2002. Nitrogen fate and transport in agricultural systems. *J. Soil Water Conserv.* 57(6): 402–408.
- Guretzky, J.A., H. Hillhouse, and J.C. MacDonald. 2023. Vegetation dynamics in nitrogen-fertilized versus mixed legume-smooth bromegrass pastures interseeded with sorghum-sudangrass. *Agron. J.* 115(2): 674–686. doi: 10.1002/agj2.21252.

- Heitman, A.J., M.S. Castillo, T.Jot. Smyth, C.R. Crozier, Z. Wang, et al. 2017. Nitrogen Fertilization Effects on Yield and Nutrient Removal of Biomass and Sweet Sorghum. *Agron. J.* 109(4): 1352–1358. doi: 10.2134/agronj2016.12.0710.
- Hillhouse, H., W. Schacht, B. Anderson, J. MacDonald, J.M. Soper, et al. 2021. Forage production and steer performance in fertilized smooth bromegrass and smooth bromegrass–legume pastures. *Crop Forage Turfgrass Manag.* 7(2): e20124. doi: 10.1002/cft2.20124.
- Holman, J.D., A. Schlegel, A.K. Obour, and Y. Assefa. 2020. Dryland cropping system impact on forage accumulation, nutritive value, and rainfall use efficiency. *Crop Sci.* 60(6): 3395–3409. doi: 10.1002/csc2.20251.
- Hood, R.C. 2001. The Effect of Soil Temperature and Moisture on Organic Matter Decomposition and Plant Growth. *Isotopes Environ. Health Stud.* 37(1): 25–41. doi: 10.1080/10256010108033279.
- Islam, M.A., J.T. Biermacher, S.M. Interrante, R.R. Reuter, A.A. Hopkins, et al. 2011. Production and Economics of Grazing Rye–Annual Ryegrass and Tall Fescue Systems. *Agron. J.* 103(2): 558–564. doi: 10.2134/agronj2010.0325.
- Kallenbach, R.L., M.S. Kerley, and G.J. Bishop-Hurley. 2006. Cumulative Forage Production, Forage Quality and Livestock Performance from an Annual Ryegrass and Cereal Rye Mixture in a Pine Walnut Silvopasture. *Agrofor. Syst.* 66(1): 43–53. doi: 10.1007/s10457-005-6640-6.

- Lauriault, L.M., R.E. Kirksey, and D.M. VanLeeuwen. 2005. Performance of Perennial Cool-Season Forage Grasses in Diverse Soil Moisture Environments, Southern High Plains, USA. *Crop Sci.* 45(3): 909–915. doi: 10.2135/cropsci2004.0280.
- Liu, P., J. Huang, O.J. Sun, and X. Han. 2010. Litter decomposition and nutrient release as affected by soil nitrogen availability and litter quality in a semiarid grassland ecosystem. *Oecologia* 162(3): 771–780. doi: 10.1007/s00442-009-1506-7.
- Mapfumo E., Naeth M.A., Baron V. S., Dick A.C., and Chanasky D. S. (2002). Grazing impacts on litter and roots: Perennial versus annual grasses. *Journal of Range Management*, 55(1): 16-22. doi: 10.2307/4003258
- Mercier K.M., C.D. Teutsch, S.R. Smith, E.L. Ritchey, and K.H. Burdine. 2021. Nitrogen fertilizer rate effects on yield and botanical components of summer annual forage mixtures. *Agron. J.* 113(3): 2798–2811. doi: 10.1002/agj2.20663.
- Naeth, M.A., A.W. Bailey, D.J. Pluth, D.S. Chanasyk, and R.T. Hardin. 1991. Grazing impacts on litter and soil organic matter in mixed prairie and fescue grassland ecosystems of Alberta. 44. doi: 10.2307/4002629.
- Nyfeler, D., O. Huguenin-Elie, M. Suter, E. Frossard, J. Connolly, et al. 2009. Strong mixture effects among four species in fertilized agricultural grassland led to persistent and consistent transgressive overyielding. *J. Appl. Ecol.* 46(3): 683–691. doi: 10.1111/j.1365-2664.2009.01653.x.
- Nyfeler, D., O. Huguenin-Elie, M. Suter, E. Frossard, and A. Lüscher. 2011. Grass–legume mixtures can yield more nitrogen than legume pure stands due to mutual

stimulation of nitrogen uptake from symbiotic and non-symbiotic sources. *Agric. Ecosyst. Environ.* 140(1): 155–163. doi: 10.1016/j.agee.2010.11.022.

Owensby, C. E. 1973. Modified step-point system for botanical composition and basal cover estimates. *Journal of Range Management* 26(4): 302-303.
doi10.2307/3896585

Redfearn D. D. Buxton D. R., Devine T. E., 1999. Sorghum intercropping effects on yield, morphology, and quality of forage soybean. *Crop Science* 39(5): 1265-1542. doi: 10.2135/cropsci1999.3951380x.

Sawargaonkar, G.L., M.D. Patil, S.P. Wani, E. Pavani, B.V.S.R. Reddy, et al. 2013. Nitrogen response and water use efficiency of sweet sorghum cultivars. *Field Crops Res.* 149: 245–251. doi: 10.1016/j.fcr.2013.05.009.

Schaefer, M.R., K.A. Albrecht, and D.M. Schaefer. 2014. Stocker Steer Performance on Tall Fescue or Meadow Fescue Alone or in Binary Mixture with White Clover. *Agron. J.* 106(5): 1902–1910. doi: 10.2134/agronj14.0075.

Sedivec, K., A. Fraase, B. Neville, D. Whitted, P. Nyren, et al. 2011. Utilizing Annual Forages in Single and Dual Cropping Systems for Late-Fall and Early Winter Grazing: Impacts on Forage Production, Cow Performance, Soil Health, and Economics.

Semenov, V.M., T.N. Lebedeva, N.B. Pautova, D.P. Khromyckina, I.V. Kovalev, et al. 2020. Relationships between the Size of Aggregates, Particulate Organic Matter

Content, and Decomposition of Plant Residues in Soil. *Eurasian Soil Sci.* 53(4): 454–466. doi: 10.1134/S1064229320040134.

Sigua, G.C., K.C. Stone, P.J. Bauer, and A.A. Szogi. 2018. Biomass and Nitrogen Use Efficiency of Grain Sorghum with Nitrogen and Supplemental Irrigation. *Agron. J.* 110(3): 1119–1127. doi: 10.2134/agronj2017.09.0533.

Smika, D.E., and P.W. Unger. 1986. Effect of Surface Residues on Soil Water Storage. In: Stewart, B.A., editor, *Advances in Soil Science*. Springer, New York, NY. p. 111–138

Tilley, J. M. A., & Terry, D. R. (1963). A two-stage technique for the in vitro digestion of forage crops. *Grass and forage science*, 18(2), 104-111. doi: 10.1111/j.1365-2494.1963.tb00335.x.

Wang, X., and F. E. Below. 1996. Cytokinins in Enhanced Growth and Tillering of Wheat Induced by Mixed Nitrogen Source. *Crop Sci.* 36(1): cropsoci1996.0011183X003600010022x. doi: 10.2135/cropsoci1996.0011183X003600010022x.

Weiss, W. P. (1994). Estimation of digestibility of forages by laboratory methods. *Forage quality, evaluation, and utilization*, 644-681. doi: 1-.2134/1994.foragequality.c16

Witzgall, K., A. Vidal, D.I. Schubert, C. Höschel, S.A. Schweizer, et al. 2021. Particulate organic matter as a functional soil component for persistent soil organic carbon. *Nat. Commun.* 12(1): 4115. doi: 10.1038/s41467-021-24192-8.

Yang, K., J. Zhu, W. Zhang, Q. Zhang, D. Lu, et al. 2022. Litter decomposition and nutrient release from monospecific and mixed litters: Comparisons of litter quality, fauna and decomposition site effects. *J. Ecol.* 110(7): 1673–1686. doi: 10.1111/1365-2745.13902.

Zhang, L., X. He, Z. Liang, W. Zhang, C. Zou, et al. 2020. Tiller development affected by nitrogen fertilization in a high-yielding wheat production system. *Crop Sci.* 60(2): 1034–1047. doi: 10.1002/csc2.20140.

**CHAPTER 3 - HERBAGE MASS RESPONSES TO SOD
SUPPRESSION WITH GLYPHOSATE IN PASTURES
INTERSEEDED WITH SORGHUM X SUDANGRASS**

Abstract

Interseeding warm-season annual forages into perennial cool-season grasses has potential to increase herbage mass and quality. Yet, methods to do so successfully remain elusive. From 2020-2022, we conducted an experiment that evaluated herbage mass responses to sod suppression after interseeding sorghum × sudangrass [*Sorghum bicolor* (L.) Moench × *S. bicolor* (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan] in three N-fertilized and three remnant, mixed legume smooth brome grass (*Bromus inermis* Leyss.) pastures. Sod-suppression treatments included glyphosate applications of 0, 0.55, 1.10, 1.65, and 2.20 kg ha⁻¹ on pastures that were heavily grazed during two rotational stocking periods in spring and an additional 0 kg ha⁻¹ glyphosate control where herbage was stockpiled throughout spring, mowed, and removed before interseeding sorghum × sudangrass. In herbage samples collected 8 weeks after treatment, perennial grass mass showed exponential decay responses as glyphosate rate increased while sorghum × sudangrass, weedy grass, and total herbage mass showed logistic growth responses. Sorghum × sudangrass reached a high of 2269 kg ha⁻¹ as glyphosate rate increased to 1.10 kg ha⁻¹ while weedy grass mass continued to increase as glyphosate rate increased to 2.20 kg ha⁻¹. Reduced perennial grass mass in herbage samples collected the next spring, though, indicated the presence of tradeoff between increasing summer herbage now and reducing next spring herbage later with glyphosate application after interseeding sorghum × sudangrass. We concluded practitioners should not use glyphosate for sod suppression before interseeding warm-season annual forages into perennial cool-season grass pastures.

Introduction

Every grassland biome experiences periods when forage growth diminishes due to abiotic factors impacting photosynthetic capacity. A community dominated by warm-season (C₄) plants will have reduced production during colder conditions (Yamori et al., 2014), whereas a cool-season (C₃) crop will experience its production shortage when conditions are hot, dry, and of high light intensity (Ehleringer and Monson, 1993). In the central United States, this period of reduced forage availability in the summer is often termed the “summer slump,” based on the lull in accumulation of cool-season forages (Denison and Perry, 1990; Ottman and Mostafa, 2014). To sustain high forage production during the summer slump, forage systems benefit from having a C₄ component in addition to the C₃ forage base. For example, in the central United States, planting annual warm-season grasses like forage sorghum [*Sorghum bicolor* (L.) Moench], sudangrass [*S. bicolor* (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan], and sorghum × sudangrass hybrids can increase forage supply (Venuto and Kindiger, 2008; Mercier et al., 2021) and nutritive value (Pedersen and Toy, 1997; Beck et al., 2007) when perennial cool-season grasses like smooth brome grass (*Bromus inermis* Leyss.) experience reduced growth (Collins and Casler, 1990; Jensen et al., 2002; Moyer and Sweeney, 2016). Additionally, these two species exhibit growth complementarity because C₃ optimum growth occurs between 20-25°C while optimum C₄ growth occurs between 38-45°C (Sage, 2002).

Including warm-season annual pastures in a grazing plan is an efficacious method to extend forage growth into summer in a cool-season grass dominated system, but it incurs an additional land requirement. Rather, a proposed method to achieve additional growth is by interseeding or sod-seeding warm-season annual forages into existing cool-season perennial pastures. This has been a successful method in previous research, significantly increasing forage

accumulation during the summer slump (Hart et al., 1971; Belesky et al., 1981). Sod-seeding is a concept which intends to introduce or add species to a system through direct seeding into established perennial pastures and rangelands without tillage (Koch et al., 1983). In the U.S., one of the most common sod-seeding examples to date is the establishment of a forage legume species into grass-dominated pastures to increase animal performance, forage yield, and economic return (Graves et al., 2012; Kelln et al., 2022). Accomplishing similar goals, sod-seeding annual grasses into thin alfalfa (*Medicago sativa* L.) stands under hay production has been shown to increase biomass production, weed suppression, and net returns (Cummings et al., 2004). These benefits have also been realized in cool-season perennial pastures under mowing regimes with successful warm-season annual grass sod-seedings (Clapham et al., 2011; Guretzky et al., 2020; Harmony and Guretzky, 2022).

Sod-seeding has certainly been shown to be effective in mowing studies, where the interseeded crop is planted into the pre-established perennial that has been cut and removed before interseeding. Less is known about the establishment success of interseeding warm season annual forages into cool-season perennial pastures where grazing is the mode of sod-suppression. Guretzky et al. (2022) used grazing as the sole method for sod-suppression and observed an increase in forage mass that primarily occurred later in the summer when growth of the existing perennial grass slowed. To further increase pasture productivity in these scenarios, they postulated that warm-season annual seedlings need to get ahead of perennial grass regrowth by either haying the perennial grass to a short stubble height or planting earlier in late May versus mid-June. Besides these, another successful method may be to couple grazing with chemical sod suppression. Other studies have utilized chemical sod-suppression to find optimal herbicide rates

for interseeding (Belesky et al., 1981; Samson and Moser, 1982; Bush et al., 1989) but not in an application coupled with grazing.

One of the most common chemicals that has been tested for use as a cool-season perennial grass sod-suppressant is glyphosate [N-(phosphonomethyl) glycine]. At rates of 1.1 kg ha⁻¹, glyphosate has been shown to suppress resident smooth brome grass growth into late summer without a total kill (Samson and Moser, 1982). At even lower rates, mid-June glyphosate application on western wheatgrass [*Pascopyrum smithii* (Rydb.) Á. Löve] in mixed pastures at rates of 0.2, 0.4, and 0.8 kg ha⁻¹ yielded 96%, 64%, and 22% of control, respectively (Lym and Kirby, 1991). In a warm-season perennial planting and sod-suppression study, glyphosate applications rates of 0.6, 0.8, and 1.1 kg ha⁻¹ were investigated (Bush et al. 1989). They found that density of planted seedlings increased with glyphosate application rate and recommended a spring application of at least 0.8 kg ha⁻¹ for an 8-week sod-suppression. With summer annual forages, it may be that the critical period of sod-suppression will be less than 8 weeks since they tend to have fast emergence (Teutsch, 2009). Using this information, our main objective was to determine if foliar-applied glyphosate could be used to temporarily suppress smooth brome grass sods following heavy grazing to accommodate sod-seeded sorghum × sudangrass emergence and summer growth. If establishment was achieved, we also wanted to determine how varying glyphosate application rates affected recovery of smooth brome grass the next spring to maintain as much perennial forage as possible.

Materials and Methods

Site History

We conducted the research in permanent pasture at the University of Nebraska-Lincoln Eastern Nebraska Research and Extension Center near Mead, Nebraska (Figure 6). The pasture,

originally seeded with smooth brome grass (*Bromus inermis* Leyss.) in 1981, received annual applications of 90 kg N ha⁻¹ as urea in late March to early April from 1985 to 2009. In 2010, the pasture was split into six, 1.2-ha pastures, and three were interseeded with a mixture of alfalfa (*Medicago sativa* L.), birdsfoot trefoil (*Lotus cornicalatus* L.), and red clover (*Trifolium pratense* L.). Of those six, three continued to receive N fertilizer (FERT) annually in spring, but the three legume-interseeded (LEG) pastures remained unfertilized. From 2012-2016, each pasture was subdivided, north to south, into six, 0.2-ha paddocks for rotational stocking of three or four crossbred steers (*Bos taurus* L.). From 2017-2019, each of the FERT and LEG pastures was subdivided into 0.6-ha, east and west halves and consequently, 0.1-ha, north to south paddocks, for a sorghum × sudangrass interseeding study (Guretzky et al., 2022). The semi-permanent fencing put in place for the 2017-2019 study remained in place for this study, but gates separating the east and west halves remained open allowing the cattle free-choice access to the whole, 0.2-ha paddock from 2020-2022. The site consisted of about 52% Tomek silt loam soil with 0-2% slopes, 28% Yutan silty clay loam soil with 2-6% slopes, and 20% Filbert silt loam soil with 0-1% slopes (USDA-NRCS, 2022).

Experimental Design

The experiment from 2020-2022 had a split-plot design with three replications (Figure 6). Main plots consisted of each FERT and LEG pasture. Subplots consisted of six different sod suppression treatments. The subplot treatments were applied within one randomly selected paddock used for rotational stocking in 2020 and an adjacent paddock in 2021 in each main plot. The sod suppression treatments consisted of spraying Roundup Powermax at 100%, 75%, 50%, and 25% of the recommended rate, i.e., 2.20 kg ha⁻¹, for glyphosate (N-(phosphonomethyl) glycine) in pastures (Samson and Moser, 1982), one grazed control, and one mowed control.

Both controls remained unsprayed, but the grazed control was managed the same as the sprayed treatments regarding vegetation height while vegetation in the mowed control was allowed to continue uninterrupted throughout the spring through use of a grazing enclosure. The subplots had a width of 1.83 m and length of 3.66 m (6.70 m²) to accommodate the sprayer and pass of a 1.52-m wide Great Plains drill.

Stocking Cycles, Interseeding, and Sod Suppression

The pastures supported four stocking cycles in 2020 and five stocking cycles in 2021. Each stocking cycle included a stocking period and a rest period in each paddock (Allen et al., 2011). In the first two stocking cycles each year, we placed the steers on the paddocks designated for application of the subplot treatments, hereafter named treatment paddock, until grazing reduced vegetation height to < 8-10 cm. The first stocking cycle began on 28 April 2020 and 1 May 2021, and the first stocking period in the treatment paddocks lasted 7 d in 2020 and 14 d in 2021. The treatment paddocks had a rest period of 22 d in 2020 and 13 d in 2021 while cattle rotated every 2-4 d among the five, nontreatment paddocks in each main plot. On 26 May 2020 and 27 May 2021, the second stocking cycle began in the treatment paddocks, and the stocking period lasted 14 d. Upon rotation of the cattle for the second stocking period in the nontreatment paddocks on 9 June 2020 and 10 June 2021, we interseeded sorghum × sudangrass cv. Super Sugar (Prairie State Seed, Wausa, NE) at a rate of 42 kg pure live seed ha⁻¹ and applied the sod suppression treatments within 48 h to the 6.70-m² subplots in the treatment paddocks (Figure 6). The drill had 19 cm row spacing and target placement depth of 1.9-3.2 cm. After sorghum × sudangrass emergence, we applied 90 kg N ha⁻¹ to the treatment paddock in the FERT main plot while the nontreatment paddocks were fertilized in early spring as was done since 1981.

To allow time for sorghum × sudangrass establishment, we provided the treatment paddocks a rest period of about 8 weeks, skipping those paddocks during the third stocking cycle, while cattle rotated twice, every 6 d through the five, nontreatment paddocks. The fourth stocking cycle resumed in the treatment paddocks on 5 August 2020 and 9 August 2021, and the stocking period lasted 6 d. In 2020, the stocking season ended after the fourth stocking cycle in the treatment paddocks because of drought. In 2021, though, the treatment paddocks had a fifth stocking cycle and 6-d stocking period from 7 to 13 September after cattle had rotated one last time every 5-6 d among the nontreatment paddocks. To maintain near equal vegetation heights among paddocks throughout each stocking season, residue heights were evaluated with ten dropdisk measurements at random locations within the treatment paddocks at the end of each stocking period (data not shown).

Herbage Mass Components

We evaluated herbage mass responses to sod suppression at two sampling times: in summer before the start of the fourth stocking cycle on 5 August 2020 and 9 August 2021 (i.e., 8 weeks after interseeding) and in the next spring on 26 May 2021 and 27 May 2022 (i.e., about 50 weeks after interseeding). During the sampling times, we hand clipped a 0.3-m² quadrat within each subplot at ground level and sorted the herbage into forage species: perennial grasses, legumes, and sorghum × sudangrass and weedy species: forbs and annual grasses other than sorghum × sudangrass. The sorted samples were then dried at 60°C in a forced-air oven for at least 48 h and weighed immediately. Upon entering the weights into a spreadsheet, we calculated dry mass of each herbage component on an area basis and grouped species to evaluate total forage species, total weedy species, and total herbage responses. Total forage species mass was computed by combining the mass of perennial grasses, legumes, and sorghum × sudangrass.

Total weedy species was computed by combining the mass of forbs and annual weedy grasses.

Total herbage mass was computed by combining the mass of total forage species and total weedy species.

Statistical Analysis

We used mixed model and nonlinear regression procedures in SAS version 9.4 for statistical analyses. In initial analyses, we analyzed the herbage mass components with an ANOVA model that included main effects and interactions of pasture type, sod suppression after interseeding treatment, sampling time after interseeding, and interseeding year. A repeated statement was included specifying that the sampling time \times year interaction was a repeated measure, and the subject was equal to the replication \times pasture type \times sod suppression after interseeding treatment interaction. Means and differences among means were computed with least square means statements, and estimate statements were made to compare the grazed versus the mowed control. Upon finding significant effects of sod suppression treatments, data for the mowed control was removed from the dataset, and new analyses were conducted to evaluate nonlinear responses of herbage mass components to glyphosate rate. The ANOVA model did not contain pasture type and its interactions for legume mass due to the absence of legumes in FERT pastures. Similarly, the ANOVA did not contain sampling time after interseeding and its interactions for sorghum \times sudangrass mass due to the absence of sorghum-sudangrass in the next spring sampling time.

Results

Weather Conditions

The historical average annual precipitation from 1968-2022 was 746 mm of rainfall but during the three years of our study, rainfall was down to 427, 711, and 438 mm in 2020, 2021,

and 2022, respectfully. Across months, precipitation remained consistently lower than the historical average except during 2021, when relatively large precipitation events during March, August, and October brought up respective rainfall accumulations by 63, 51, and 53% above their averages (Figure 6). The average annual temperatures for 2020, 2021, and 2022 were 10.4, 10.7, and 9.8 °C, respectively while the long term average temperature was 10.2 °C. In 2021, the average temperature would have been higher if February temperatures had not declined to -10.2 °C as long term average temperatures in this month are typically around -3.4 °C. Otherwise, temperature variability across months were reflected in the year's respective average.

Analysis of Variance

Pasture type did not influence herbage mass components in the summer sampling after interseeding and sod suppression (Table 34). However, it did affect perennial grass and weedy forb mass in the next spring sampling. It also had an influence on weedy grass mass in the next spring sampling within the context of a three-way interaction with sod suppression after interseeding treatment and interseeding year (Table 34). Sod suppression after interseeding, meanwhile, had an influence on several herbage mass components including perennial grasses, legumes, sorghum-sudangrass, weedy grasses, and total herbage in the summer sampling and perennial grasses and total herbage in the next spring sampling (Table 34). Interseeding year also influenced several components in the summer and next spring samplings.

Pasture Type Effects

The N-fertilized and remnant mixed-legume pastures had similar perennial grass mass in the summer sampling after interseeding and sod suppression (1493 kg ha⁻¹), but in the next spring sampling, the N-fertilized pastures had 28% greater perennial grass mass than the remnant

mixed-legume pastures (3539 and 2758 kg ha⁻¹, respectively; $P < 0.002$). Weedy forb mass, on the other hand, showed opposite responses to pasture type where it averaged 118 kg ha⁻¹ in N-fertilized pastures compared to 397 kg ha⁻¹ in remnant mixed-legume pastures in the next spring after interseeding and sod suppression ($P = 0.062$).

Sod Suppression After Interseeding Effects

Summer After Treatment

Among the 0 kg ha⁻¹ glyphosate controls, mowing and removing herbage that had been stockpiled did not affect perennial grass mass later that summer relative to heavily grazing the herbage in two rotational stocking periods in spring before interseeding sorghum × sudangrass in either the 2020 (1755 vs. 2028 kg ha⁻¹, respectively; $P = 0.431$) or 2021 (2737 vs. 2956 kg ha⁻¹, respectively; $P = 0.487$) treatment years. Applying glyphosate after interseeding pastures with sorghum × sudangrass, though, significantly reduced perennial grass mass relative to the grazed 0 kg ha⁻¹ control in the summer sampling (Figure 8). Indeed, perennial grass mass showed a significant fit with an exponential decay model as glyphosate rate increased in the 2020 ($y = 2015.3e^{-0.4806x}$) and 2021 ($y = 2805.4e^{-0.8084x}$) treatment years.

Legume mass depended on the sod suppression after interseeding treatment in the summer sampling (Table 34), but it did not show a significant quantitative relationship with glyphosate rate, nor did it differ between any of the glyphosate rates and the grazed 0 kg ha⁻¹ control (data not shown). Mowing and removing herbage that had been stockpiled, though, increased legume mass later that summer by 116% relative to heavily grazing the herbage in two stocking periods in spring before interseeding sorghum × sudangrass in the 0 kg ha⁻¹ glyphosate controls (331 vs. 153 kg ha⁻¹, respectively; $P = 0.039$).

Sorghum × sudangrass mass, meanwhile, showed a logistic growth response to increasing glyphosate rate after interseeding (Figure 9; $y = 2269.4 \div (1 + 12.1119e^{-6.5564x})$; $P < 0.001$). Indeed, sorghum × sudangrass mass increased from 126 kg ha⁻¹ in the grazed, 0 kg ha⁻¹ control to 2338 kg ha⁻¹ in the 2.20 kg ha⁻¹ glyphosate treatment. Between the 0.55 and 1.10 kg ha⁻¹ treatments, sorghum × sudangrass mass reached a maximum and plateaued with increasing glyphosate rate. Among the 0 kg ha⁻¹ controls, mowing and removing herbage that had been stockpiled did not affect sorghum × sudangrass mass later that summer relative to heavily grazing the herbage during rotational stocking periods in spring before interseeding (230 and 114 kg ha⁻¹, respectively; $P = 0.884$).

In the summer sampling, weedy grass mass ($y = 1289.2 \div (1 + 0.7687e^{-0.9559x})$) and total herbage mass ($y = 4701.5 \div (1 + 0.3271e^{-2.8482x})$) also had significant fits with logistic growth models as glyphosate rate increased (Figure 9; $P < 0.001$). Mowing and removing herbage that had been stockpiled, though, reduced weedy grass mass later that summer by 90% relative to heavily grazing the herbage during two rotational stocking periods in spring before interseeding sorghum × sudangrass in the 0 kg ha⁻¹ controls (79 vs. 750 kg ha⁻¹, respectively; $P = 0.063$). Total herbage mass, meanwhile, increased above the 0 kg ha⁻¹ grazed control when glyphosate applied reached 1.1 kg ha⁻¹. Mowing and removing herbage that had been stockpiled did not significantly affect total herbage mass later that summer relative to heavily grazing the herbage during two rotational stocking periods in spring before interseeding sorghum × sudangrass in the 0 kg ha⁻¹ controls (2983 vs. 3555 kg ha⁻¹, respectively; $P = 0.393$).

Next Spring After Treatment

In the next spring sampling, perennial grass mass did not depend on a sod suppression × treatment year interaction as it did in the previous summer (Table 34). However, perennial grass

mass again showed a significant fit with an exponential decay model in response to increasing glyphosate rate (Figure 10; $y = 4302.2e^{-0.3339x}$; $P < 0.001$). Mowing and removing herbage that had been stockpiled also reduced perennial grass mass the next spring compared to heavily grazing the herbage in two rotational stocking cycles the previous spring before interseeding sorghum × sudangrass in the 0 kg ha⁻¹ controls (3488 and 4305 kg ha⁻¹, respectively; $P = 0.061$). Legume mass in the next spring sampling, meanwhile, did not vary with the sod suppression treatment as it did in the previous summer sampling (Table 34). Mowing and removing herbage that had been stockpiled also did not affect legume mass the next spring compared to heavily grazing the herbage in two rotational stocking cycles the previous spring before interseeding sorghum × sudangrass in the 0 kg ha⁻¹ controls (84 and 44 kg ha⁻¹, respectively; $P = 0.430$).

Total herbage mass showed a contrasting response to the sod suppression treatments in the next spring sampling (Figure 10) relative to the sampling in the previous summer (Figure 9). Total herbage mass showed an exponential decay response ($y = 4357.3e^{-0.221x}$; $P < 0.001$) with increasing glyphosate rate in the next spring sampling, decreasing by 23% relative to the grazed 0 kg ha⁻¹ control when the glyphosate rate reached 1.1 kg ha⁻¹ (Figure 10). Among 0 kg ha⁻¹ controls, mowing and removing herbage that had stockpiled reduced total herbage mass relative to heavily grazing the herbage in two rotational stocking cycles the previous spring before interseeding sorghum × sudangrass (3578 vs. 4478 kg ha⁻¹, respectively). In the next spring sampling, weedy grass mass ranged from 0 to 2 kg ha⁻¹ among all but one subplot. An outlier in the subplot that received glyphosate at 1.10 kg ha⁻¹ in the 2021 treatment year, where weedy grass mass averaged 19 kg ha⁻¹, resulted in the pasture type × sod suppression after interseeding × year interaction (Table 34).

Treatment Year Effects

The treatment year for sod suppression and interseeding sorghum × sudangrass affected a few herbage mass components. As described above, perennial grass mass depended on a sod suppression after interseeding × treatment year interaction in the summer sampling, and on average across sod suppression after interseeding treatments, the 2021 treatment year had 20% greater perennial grass mass than the 2020 treatment year (Table 35). In the next spring sampling, though, the 2020 treatment year was found to have greater perennial grass mass than the 2021 treatment year (Table 35). Weedy forb mass and weedy grass mass, in contrast, increased from the 2020 to 2021 treatment year in the summer and next spring samplings (Table 35). Total herbage mass, meanwhile, reflected perennial grass mass increasing from the 2020 to 2021 treatment year in the summer sampling but decreasing from the 2020 to 2021 treatment year in the next spring sampling (Table 35).

Discussion

This study expanded current literature on methods to improve interseeding of warm-season annual forages into perennial cool-season grass pastures. The best practice has been to interseed the annual forage following mowing and removal of the perennial grass, such as with a hay harvest, after it reaches a reproductive stage in late spring. Late spring plantings should enhance warm-season annual forage success as cool-season perennial grass growth rates start to diminish as temperatures increase through summer. The practice, though, has had variable success depending on the year and moisture availability (Guretzky et al., 2020; Harmony and Guretzky, 2022), and in some pasture situations, grazing instead of mechanical removal of existing herbage may be necessary (Guretzky et al., 2023). Grazing techniques implemented in this study to reduce local perennial pasture species competition on sod-seeded sorghum ×

sudangrass included use of two heavy-grazing events on all experimental areas. Stocking periods one and two were intended to deplete leaf area and root carbohydrate reserves and thereby enhance competitive success of sorghum × sudangrass after interseeding.

We observed that mowing and removing herbage that has been stockpiled throughout spring, such as might be done under a haying regime, did not result in a gain or loss in total herbage mass in the summer sampling compared to heavily grazing the herbage in two stocking periods in spring before interseeding sorghum × sudangrass. In both interseeding years in this experiment, 2020 and 2021, precipitation was below average at planting in June (Figure 7), which may have limited success of sorghum × sudangrass under both situations. Sorghum × sudangrass mass was similarly low in the controls whether herbage was mowed and removed or heavily grazed before interseeding. Mowing as the form of sod suppression, though, also failed to increase total forage accumulation above baseline levels in an experiment where cowpea [*Vigna unguiculata* (L.) Walp.] was sod-seeded into newly seeded tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] pastures in a year with above average growing season precipitation (Nave et al., 2020). This was also seen in another experiment sod-seeding cowpea into tall fescue pastures with no sod-suppression (Corbin et al., 2019).

Considering the variable success of interseeding warm-season annual forages into existing perennial cool-season grass pastures, whether in past studies or the current one, we evaluated whether chemical suppression of sod would improve interseeding. Different rates of glyphosate were applied in conjunction with the heavy grazing events to suppress existing sod before interseeding. We found that the use of glyphosate improved sorghum × sudangrass mass in summer, 8 weeks after interseeding. As glyphosate rates increased, though, sorghum × sudangrass mass showed logistic growth rather than a linear response indicating that full rates of

herbicide were unnecessary to improve interseeding success. Sorghum-sudangrass mass reached a plateau at 1.10 kg ha⁻¹ glyphosate applied.

The danger from use of an herbicide compared to mechanical or grazing removal of herbage before interseeding, without use of an herbicide, is lasting harm to the perennial grass. As expected, perennial grass mass declined in response to increasing glyphosate rate in the summer sampling, 8 weeks after sorghum × sudangrass interseeding, indicating success of the sod suppression treatments. However, the carryover of increasing glyphosate rates on perennial grass mass to the next spring sampling is troubling as it shows a failure of the perennial grass to recover, ultimately negating the benefit of sorghum × sudangrass interseeding.

Low precipitation in fall 2020 and spring 2021 may have affected the ability smooth brome grass to recover from the glyphosate suppression after interseeding treatments, especially after experiencing a previous spring and summer deficient in precipitation. In September, October, November, and December, cumulative precipitation was 118 mm whereas historical average was 198 mm (Figure 7). In 2021, spring rains were variable as March received above average precipitation at 104 mm, April received 0 mm, and May received below average rainfall at 81 mm. After the second interseeding year of the study, rainfall was much greater in August and October 2021, but in the next spring, precipitation was near average in March, 39% lower than average in April, and slightly below average in May, indicating this study took place during a multi-year drought before its completion in May 2022.

During the summer sampling, pasture type had no impact on perennial grass mass but in the next spring sampling, the N-fertilized pastures had greater perennial grass mass than the remnant, mixed-legume pastures. This is likely because in the spring, cool-season species have higher growth rates and N requirements than during summer months. Consequently, N

fertilization likely aided in perennial grass recovery during the following year. Legumes, meanwhile, occupied only a small percentage of herbage mass in the remnant, mixed-legume pastures (~3%), and glyphosate rates had no detectible influence on their mass. In our study alfalfa appeared to make up the majority of legume mass, and a study has shown that applications of glyphosate at 0.48 kg ha^{-1} on vegetative alfalfa significantly reduce its mass compared to an untreated control (Arregui et al., 2001). The glyphosate effect in our study could have been undetected due to the low and variable legume mass since alfalfa plants were sparsely distributed in the field. However, mowing and removing herbage that had been stockpiled throughout spring improved legume mass in the summer sampling compared to heavily grazing the herbage in two stocking periods in spring before interseeding sorghum \times sudangrass indicating that heavily grazing alfalfa with short rest periods may negatively affect its productivity.

Spring seems to be unproblematic time for both weedy grasses and forbs. However, once summer reduces the growth and competition from cool season forage species such as smooth brome grass, weedy grasses become abundant. During the summer sampling after sod suppression, weedy grasses were present at 750 kg ha^{-1} in the control and increased by $\sim 400 \text{ kg ha}^{-1}$ at glyphosate rates exceeding 1.10 kg ha^{-1} . Reducing perennial grass competition with glyphosate likely benefitted the weeds which likely reduced the growth potential of the interseeded sorghum \times sudangrass. However, the pasture weeds may be advantageous to a grazing system by increasing herbage mass and nutritive value during the summer slump. In our study, the weedy grasses appeared to consist primarily of yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.) and crabgrass (*Digitaria sanguinalis* (L.) Scop.). Bunton et al. (2019) tested nutritive values of common pasture weeds throughout the summer and found that large crabgrass

had greater in vitro true digestibility (IVTD) across the entire summer than tall fescue while yellow foxtail had greater IVTD until August 28th. When more glyphosate was applied, herbage mass in the summer exceeded the control. The marked increase in total herbage mass caused by weedy species could mean more grazing days for practitioners during summer months, though they should be aware that weedy grasses can be difficult to manage for forage quality.

Regardless, next spring herbage mass diminished with more glyphosate and thus grazing days will be reduced with glyphosate rates at 1.1 kg ha⁻¹ and above. Weedy grass and total herbage mass also showed logistic growth responses to increasing glyphosate rates indicating greater overall productivity of the system in the summer sampling.

Although we did not have unseeded controls in this study, previous research at this study site has not observed effects of interseeding sorghum × sudangrass on legume mass, but unseeded areas have 22% greater perennial grass mass than interseeded areas (Guretzky et al. 2023). This would mean an unseeded, grazed control likely would have had a perennial grass mass in the summer sampling ranging from 2475 to 3606 kg ha⁻¹ depending on the interseeding year (Figure 8; 2029 or 2956 × 1.22). Sorghum × sudangrass interseeding also has reduced weedy grass mass in previous studies using grazing (Guretzky et al., 2023) and mowing (Guretzky et al., 2020) as the principle means of sod suppression. Without sorghum × sudangrass interseeding, weedy grass mass in the summer sampling likely would have been 32% greater, i.e., 990 kg ha⁻¹ (Figure 8; 750 × 1.32) in the grazed control. In an unseeded control where herbage was mowed and removed after stockpiling throughout spring, weedy grass mass in the summer sampling likely would have been 1% to 56% greater, i.e., 80 to 123 kg ha⁻¹ compared to 79 kg ha⁻¹ in the mowed and interseeded control, depending on the year based on annual weed mass reported in Guretzky et al. (2020).

Conclusions

These data suggest that increasing glyphosate rates as a means of sod suppression to improve sorghum × sudangrass interseeding into existing perennial grass pastures reduces perennial grass growth during summer and does not allow recovery by the next spring. As glyphosate rate applied to perennial grass is increased, sorghum × sudangrass and total herbage mass shows logistic rather than linear growth, reaching a plateau at 1.10 kg ha⁻¹ of glyphosate applied. Therefore, our recommendation to practitioners is to interseed a pasture with warm-season annual forages only if existing herbage can be mowed and removed after stockpiling throughout spring before interseeding and subsequent moisture is expected to be plentiful. When using glyphosate, expect more herbage mass to be weedy grasses than when using mowing or solely grazing for sod suppression. Glyphosate use also will reduce perennial grass mass the next spring, a penalty offsetting any increased herbage gains in summer due to sorghum × sudangrass interseeding. When haying smooth brome grass or utilizing glyphosate as a chemical suppressant, we recommend fertilizing pastures with 90 kg N ha⁻¹ in the spring to improve perennial grass recovery. If pastures contain a higher proportion of legumes, springtime N fertilization may be unnecessary due to symbiotic N₂ fixation and subsequent N cycling through rhizosphere exchange, cattle defecation, and urination.

Literature Cited

- Allen, V. G., Batello, C., Berretta, E. J., Hodgson, J., Kothmann, M., Li, X., McIvor, J., Milne, J., Morris, C., Peeters, A., & Sanderson, M. (2011). An international terminology for grazing lands and grazing animals. *Grass & Forage Science*, 66, 2–29. doi: 10.1111/j.1365-2494.2010.00780.x
- Arregui, M.C., D. Sánchez, and R. Scotta. 2001. Weed Control in Established Alfalfa (*Medicago sativa*) with Postemergence Herbicides. *Weed Technol.* 15(3): 424–428. doi: 10.1614/0890-037X(2001)015[0424:WCIEAM]2.0.CO;2.
- Beck, P.A., S. Hutchison, S.A. Gunter, T.C. Losi, C.B. Stewart, et al. 2007. Chemical composition and in situ dry matter and fiber disappearance of sorghum × Sudangrass hybrids. *J. Anim. Sci.* 85(2): 545–555. doi: 10.2527/jas.2006-292.
- Belesky, D.P., S.R. Wilkinson, R.N. Dawson, and J.E. Elsner. 1981. Forage Production of a Tall Fescue Sod Intercropped with Sorghum × Sudangrass and Rye. *Agron. J.* 73(4): 657–660. doi: 10.2134/agronj1981.00021962007300040021x.
- Bunton, G., Trower, Z., Roberts, C. and Bradley, K.W. 2020. Seasonal changes in forage nutritive value of common weeds encountered in Missouri pastures. *Weed technology*, 34(2): 164-171. doi: 10.1017/wet.2019.89
- Bush, B.L., S.S. Waller, B.E. Anderson, L.E. Moser, and R.M. Wozniak. 1989. Sod Seeded Warm-Season Grass With and Without Sod Suppression. *Proc. North Am. Prairie Conf.* <https://digitalcommons.unl.edu/napcproceedings/48>.

- Clapham, W., J. Fedders, and O. Abaye. 2011. Interseeding Teff Into Tall Fescue Swards to Improve Late Summer Forage Production - Clapham - 2011 - Forage & Grazinglands - Wiley Online Library.
<https://access.onlinelibrary.wiley.com/doi/full/10.1094/FG-2011-1128-01-RS> (accessed 11 January 2023).
- Collins, M., and M.D. Casler. 1990. Forage quality of five cool-season grasses. II. Species effects. *Anim. Feed Sci. Technol.* 27(3): 209–218. doi: 10.1016/0377-8401(90)90083-K.
- Corbin, M.D., R.L.G. Nave, G.E. Bates, D.M. Butler, and S.A. Hawkins. 2019. Alternatives to Conventional Nitrogen Fertilization on Tall Fescue and Bermudagrass. *Agron. J.* 111(1): 275–286. doi: 10.2134/agronj2018.03.0190.
- Cummings, D., R.C. Berberet, J.F. Stritzke, and J.L. Caddel. 2004. Sod-Seeding and Grazing Effects on Alfalfa Weevils, Weeds, and Forage Yields in Established Alfalfa. *Agron. J.* 96(5): 1216–1221. doi: 10.2134/agronj2004.1216.
- Denison, R.F., and H.D. Perry. 1990. Seasonal Growth Rate Patterns for Orchardgrass and Tall Fescue on the Appalachian Plateau. *Agron. J.* 82(5): 869–873. doi: 10.2134/agronj1990.00021962008200050004x.
- Ehleringer, J.R., and R.K. Monson. 1993. Evolutionary and Ecological Aspects of Photosynthetic Pathway Variation. *Annu. Rev. Ecol. Syst.* 24: 411–439.
- Graves, M.E., N. McLean, G. Jones, and R.C. Martin. 2012. Pasture and sheep performance response to sod-seeding red clover (*Trifolium pratense* L.) or white clover (*Trifolium*

- repens L.) into naturalized pastures in eastern Canada. *Anim. Feed Sci. Technol.* 177(1): 7–14. doi: 10.1016/j.anifeedsci.2012.06.006.
- Guretzky, J.A., H. Hillhouse, and J.C. MacDonald. 2023. Vegetation dynamics in nitrogen-fertilized versus mixed legume-smooth bromegrass pastures interseeded with sorghum-sudangrass. *Agron. J.* 115(2): 674–686. doi: 10.1002/agj2.21252.
- Guretzky, J.A., J.D. Volesky, M.B. Stephenson, K.R. Harmony, and J.L. Moyer. 2020. Interseeding annual warm-season grasses into temperate pasturelands: Forage accumulation and composition. *Agron. J.* 112(4): 2812–2825. doi: 10.1002/agj2.20250.
- Harmony, K., and J. Guretzky. 2022. Interseeding Sorghum-Sudangrass into Perennial Cool-Season Western Wheatgrass Pasture. *Kans. Agric. Exp. Stn. Res. Rep.* 8(2). doi: 10.4148/2378-5977.8276.
- Hart, R.H., H.J. Retzer, R.F. Dudley, and G.E. Carlson. 1971. Seeding Sorghum × Sudangrass Hybrids into Tall Fescue Sod1. *Agron. J.* 63(3): 478–480. doi: 10.2134/agronj1971.00021962006300030039x.
- Jensen, K.B., D.A. Johnson, K.H. Asay, and K.C. Olson. 2002. Seasonal-accumulated growth and forage quality of range grasses for fall and winter grazing. *Can. J. Plant Sci.* 82(2): 329–336. doi: 10.4141/P01-009.
- Kelln, B.M., G.B. Penner, S.N. Acharya, T.A. McAllister, K. Larson, et al. 2022. Effect of sod-seeding bloat-free legumes on pasture productivity, steer performance, and production economics. *Can. J. Anim. Sci.* 102(2): 352–367. doi: 10.1139/cjas-2021-0098.

- Koch, D.W., G.W. Mueller-Warrant, and New Hampshire Agricultural Experiment Station. 1983. Sod seeding of forages, Station Bulletin, no.525.
- Lym, R.G., and D.R. Kirby. 1991. Effect of Glyphosate on Introduced and Native Grasses. *Weed Technol.* 5(2): 421–425. doi: 10.1017/S0890037X00028359.
- Mercier, K.M., C.D. Teutsch, S.R. Smith, E.L. Ritchey, K.H. Burdine, et al. 2021. Nitrogen fertilizer rate effects on yield and botanical components of summer annual forage mixtures. *Agron. J.* 113(3): 2798–2811. doi: 10.1002/agj2.20663.
- Moyer, J., and D. Sweeney. 2016. Growth and Forage Quality Responses of Smooth Brome grass to Nitrogen Placement and Timing. *Agron. J.* 108(6): 2453–2461. doi: 10.2134/agronj2015.0503.
- Nave, R.L.G., M.P. Quinby, A.P. Griffith, M.D. Corbin, and G.E. Bates. 2020. Forage mass, nutritive value, and economic viability of cowpea overseeded in tall fescue and sorghum-sudangrass swards. *Crop Forage Turfgrass Manag.* 6(1): e20003. doi: 10.1002/cft2.20003.
- Ottman, M., and A. Mostafa. 2014. Summer Slump in Alfalfa. *CALS Publ. Arch. Univ. Ariz.* <https://repository.arizona.edu/handle/10150/311219> (accessed 9 January 2023).
- Pedersen, J.F., and J.J. Toy. 1997. Forage Yield, Quality, and Fertility of Sorghum × Sudan Grass Hybrids in A1 and A3 Cytoplasm. *Crop Sci.* 37(6): crops1997.0011183X003700060049x. doi: 10.2135/cropsci1997.0011183X003700060049x.

- Sage, R.F. 2002. Variation in the *k_c* of Rubisco in C₃ and C₄ plants and some implications for photosynthetic performance at high and low temperature. *J. Exp. Bot.* 53(369): 609–620. doi: 10.1093/jexbot/53.369.609.
- Samson, J.F., and L.E. Moser. 1982. Sod-Seeding Perennial Grasses into Eastern Nebraska Pastures I. *Agron. J.* 74(6): 1055–1060. doi: 10.2134/agronj1982.00021962007400060029x.
- Teutsch, C. 2009. Warm-Season Annual Grasses for Summer Forage.
- Venuto, B., and B. Kindiger. 2008. Forage and biomass feedstock production from hybrid forage sorghum and sorghum–sudangrass hybrids. *Grassl. Sci.* 54(4): 189–196. doi: 10.1111/j.1744-697X.2008.00123.x.
- Yamori, W., K. Hikosaka, and D.A. Way. 2014. Temperature response of photosynthesis in C₃, C₄, and CAM plants: temperature acclimation and temperature adaptation. *Photosynth. Res.* 119(1–2): 101–117. doi: 10.1007/s11120-013-9874-6.
- Guretzky, J.A., J.D. Volesky, M.B. Stephenson, K.R. Harmony, and J.L. Moyer. 2020. Interseeding annual warm-season grasses into temperate pasturelands: Forage accumulation and composition. *Agron. J.* 112(4): 2812–2825. doi: 10.1002/agj2.20250.
- Harmony, K., and J. Guretzky. 2022. Interseeding Sorghum-Sudangrass into Perennial Cool-Season Western Wheatgrass Pasture. *Kans. Agric. Exp. Stn. Res. Rep.* 8(2). doi: 10.4148/2378-5977.8276.

- Hart, R.H., H.J. Retzer, R.F. Dudley, and G.E. Carlson. 1971. Seeding Sorghum × Sudangrass Hybrids into Tall Fescue Sod1. *Agron. J.* 63(3): 478–480. doi: 10.2134/agronj1971.00021962006300030039x.
- Jensen, K.B., D.A. Johnson, K.H. Asay, and K.C. Olson. 2002. Seasonal-accumulated growth and forage quality of range grasses for fall and winter grazing. *Can. J. Plant Sci.* 82(2): 329–336. doi: 10.4141/P01-009.
- Kelln, B.M., G.B. Penner, S.N. Acharya, T.A. McAllister, K. Larson, et al. 2022. Effect of sod-seeding bloat-free legumes on pasture productivity, steer performance, and production economics. *Can. J. Anim. Sci.* 102(2): 352–367. doi: 10.1139/cjas-2021-0098.
- Koch, D.W., G.W. Mueller-Warrant, and New Hampshire Agricultural Experiment Station. 1983. Sod seeding of forages, Station Bulletin, no.525.
- Lym, R.G., and D.R. Kirby. 1991. Effect of Glyphosate on Introduced and Native Grasses. *Weed Technol.* 5(2): 421–425. doi: 10.1017/S0890037X00028359.
- Mercier, K.M., C.D. Teutsch, S.R. Smith, E.L. Ritchey, K.H. Burdine, et al. 2021. Nitrogen fertilizer rate effects on yield and botanical components of summer annual forage mixtures. *Agron. J.* 113(3): 2798–2811. doi: 10.1002/agj2.20663.
- Moyer, J., and D. Sweeney. 2016. Growth and Forage Quality Responses of Smooth Bromegrass to Nitrogen Placement and Timing. *Agron. J.* 108(6): 2453–2461. doi: 10.2134/agronj2015.0503.

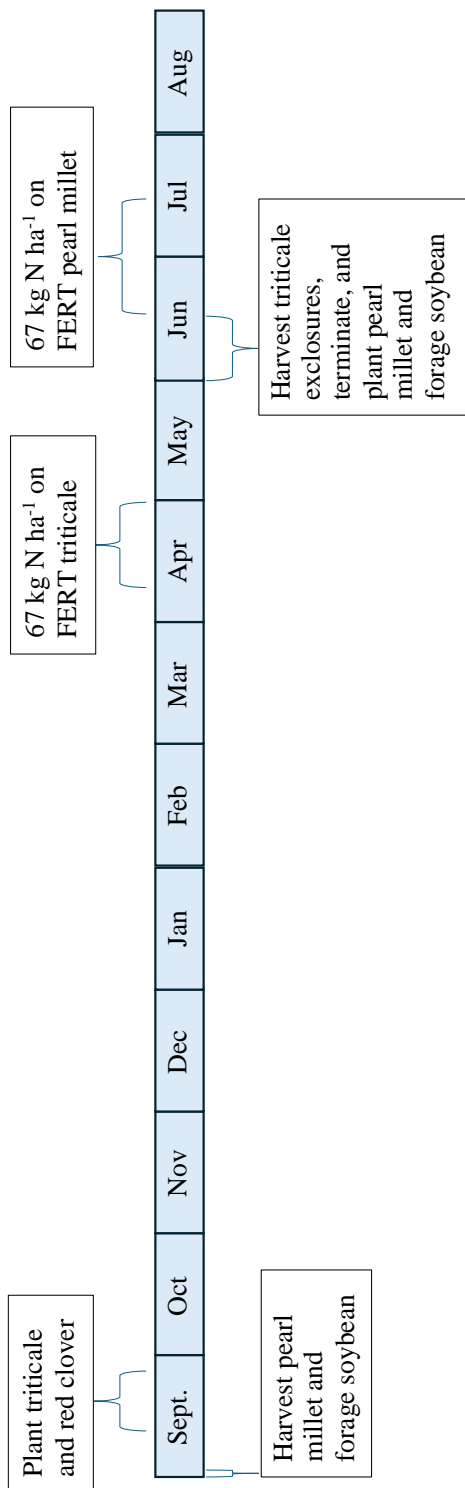
- Nave, R.L.G., M.P. Quinby, A.P. Griffith, M.D. Corbin, and G.E. Bates. 2020. Forage mass, nutritive value, and economic viability of cowpea overseeded in tall fescue and sorghum-sudangrass swards. *Crop Forage Turfgrass Manag.* 6(1): e20003. doi: 10.1002/cft2.20003.
- Ottman, M., and A. Mostafa. 2014. Summer Slump in Alfalfa. *CALS Publ. Arch. Univ. Ariz.* <https://repository.arizona.edu/handle/10150/311219> (accessed 9 January 2023).
- Pedersen, J.F., and J.J. Toy. 1997. Forage Yield, Quality, and Fertility of Sorghum × Sudan Grass Hybrids in A1 and A3 Cytoplasm. *Crop Sci.* 37(6): crops1997.0011183X003700060049x. doi: 10.2135/crops1997.0011183X003700060049x.
- Sage, R.F. 2002. Variation in the *k_{cat}* of Rubisco in C3 and C4 plants and some implications for photosynthetic performance at high and low temperature. *J. Exp. Bot.* 53(369): 609–620. doi: 10.1093/jexbot/53.369.609.
- Samson, J.F., and L.E. Moser. 1982. Sod-Seeding Perennial Grasses into Eastern Nebraska Pastures1. *Agron. J.* 74(6): 1055–1060. doi: 10.2134/agronj1982.00021962007400060029x.
- Teutsch, C. 2009. Warm-Season Annual Grasses for Summer Forage.
- Venuto, B., and B. Kindiger. 2008. Forage and biomass feedstock production from hybrid forage sorghum and sorghum–sudangrass hybrids. *Grassl. Sci.* 54(4): 189–196. doi: 10.1111/j.1744-697X.2008.00123.x.

Yamori, W., K. Hikosaka, and D.A. Way. 2014. Temperature response of photosynthesis in C3, C4, and CAM plants: temperature acclimation and temperature adaptation. *Photosynth. Res.* 119(1–2): 101–117. doi: 10.1007/s11120-013-9874-6.

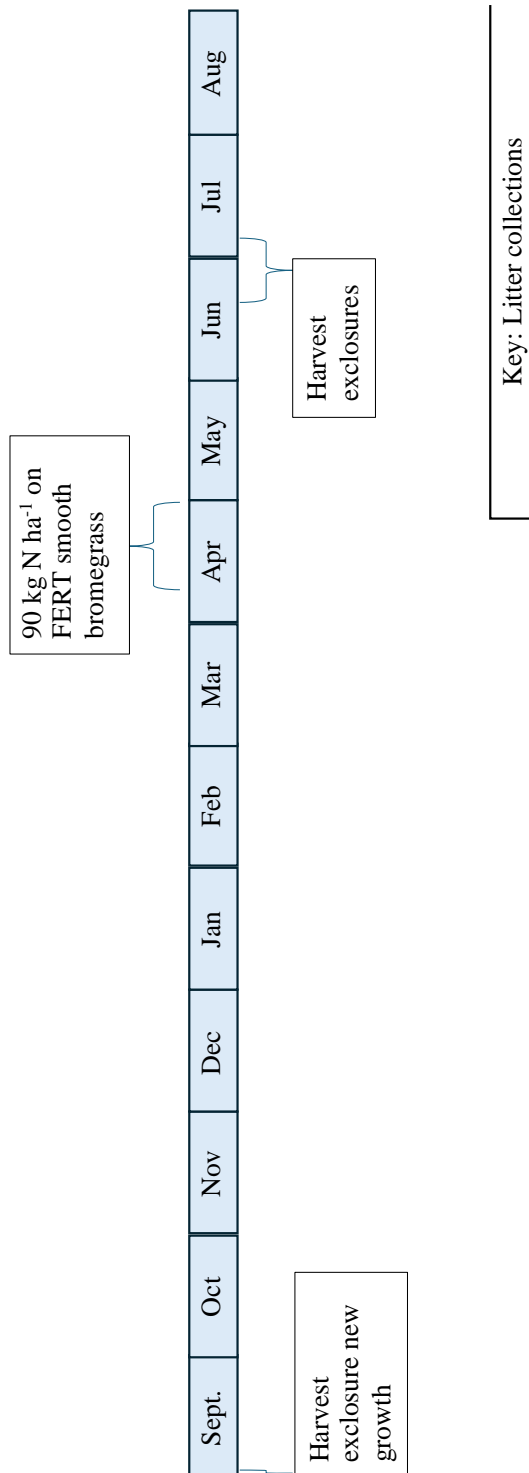
FIGURES

Figure 1. Treatment and data collection timeline for the Double Cropped Annual Forage System and the Diverse Perennial Circular Forage System.

Double Cropped Annual Forage System



Diverse Perennial Circular Forage System



Key: Litter collections

Figure 2. Average monthly precipitation of the study years from August 2021 to September 2023 and their 30-year averages at Ithaca, Nebraska.

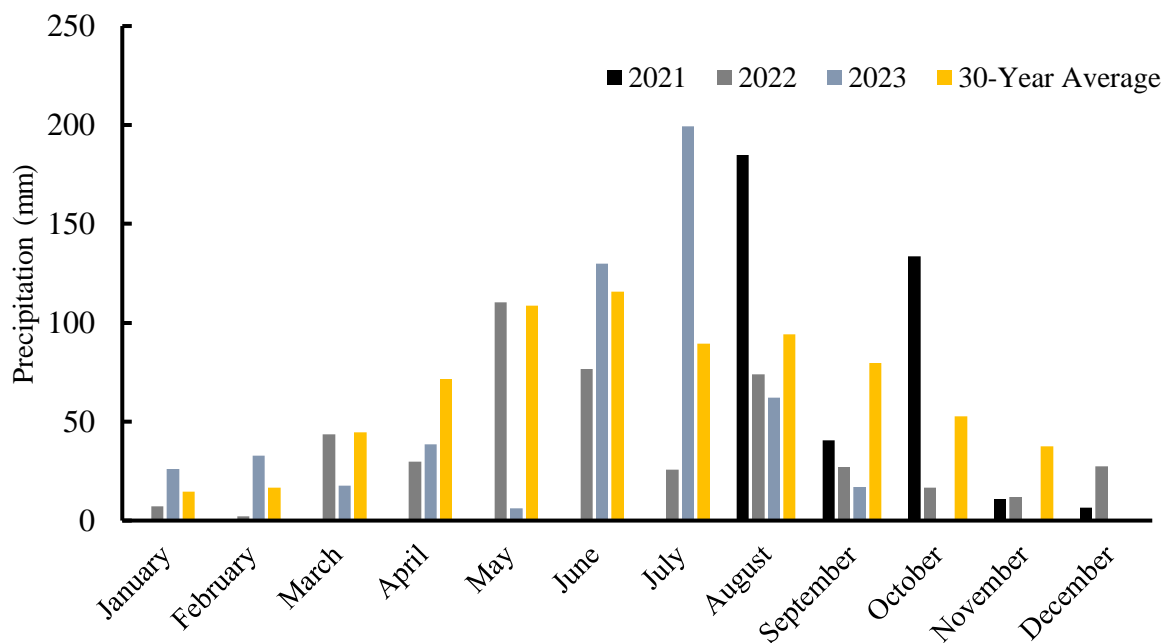


Figure 3. Average monthly temperatures of the study years from August 2021 to September 2023 at Ithaca, Nebraska.

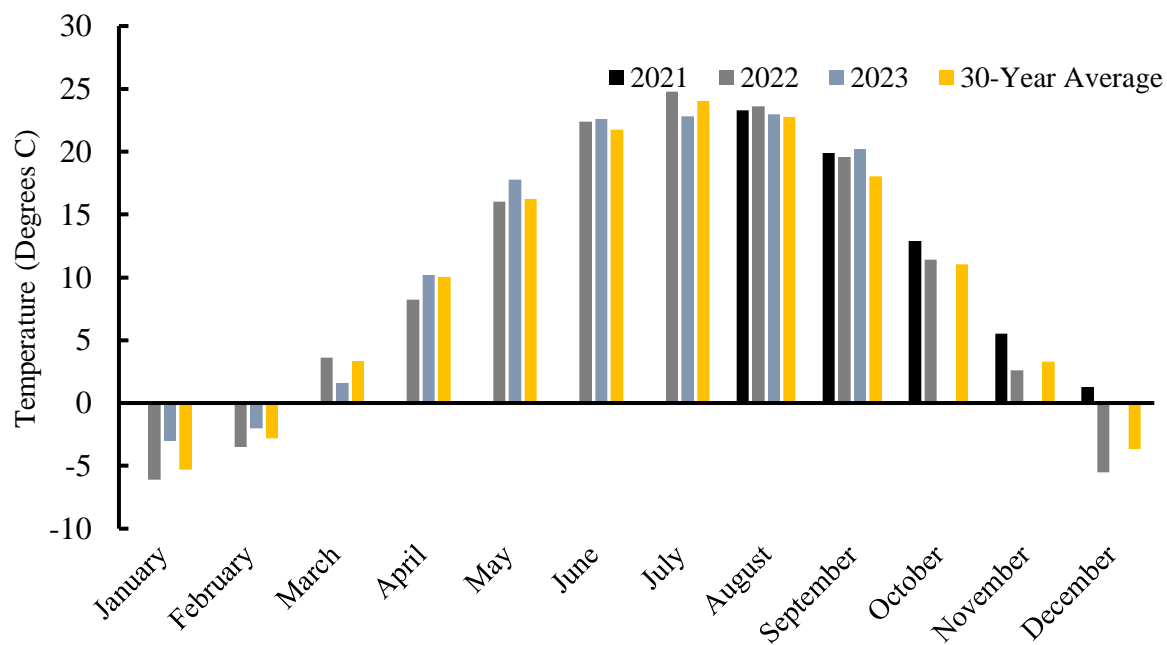


Figure 4. Bare ground and litter cover averaged across N fertilized grass and mixed grass-legume pastures expressed as percentages of basal cover in the double cropped annual forage system (DCAFS) in 2022 (a) and 2023 (b).

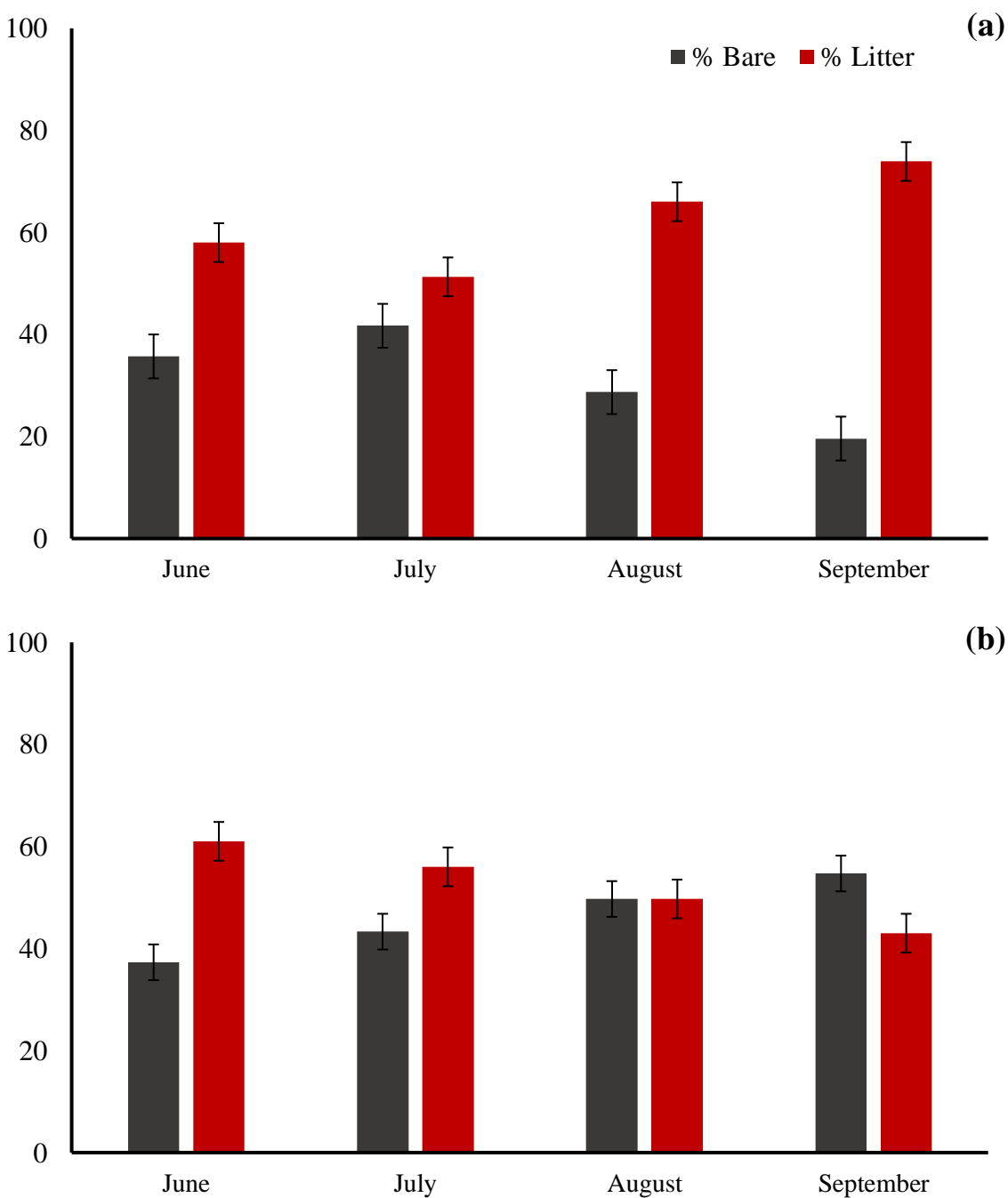


Figure 5. Bare ground and litter cover averaged across N fertilized grass and mixed grass-legume pastures expressed as percentages of basal cover in the diverse perennial circular forage system (DPCFS) in 2022 (a) and 2023 (b).

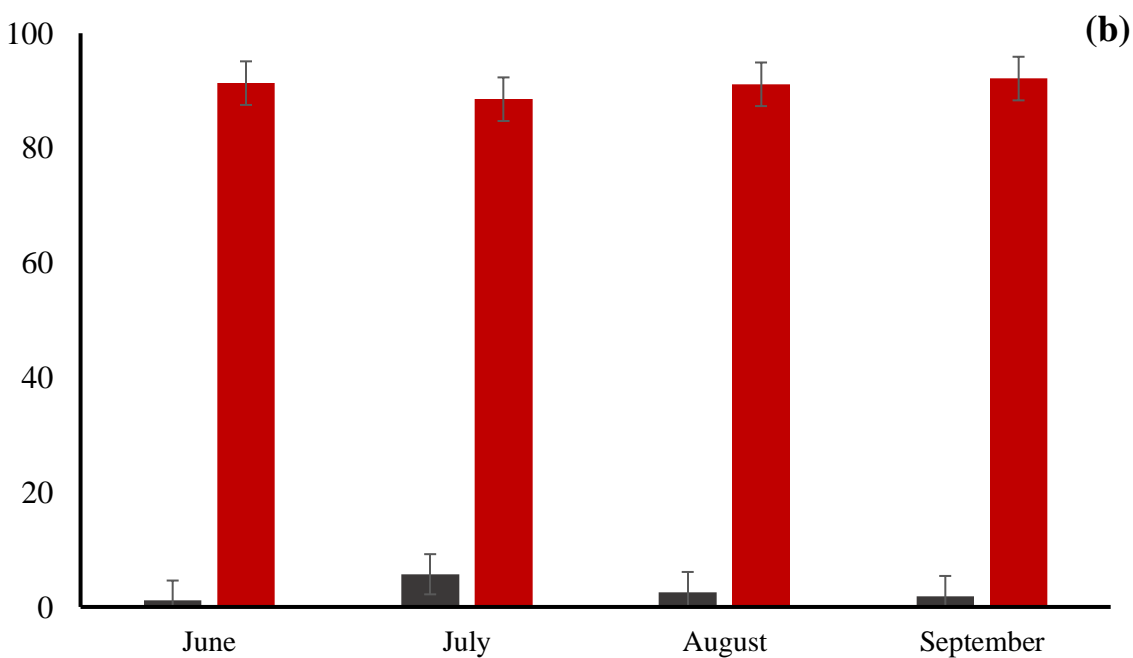
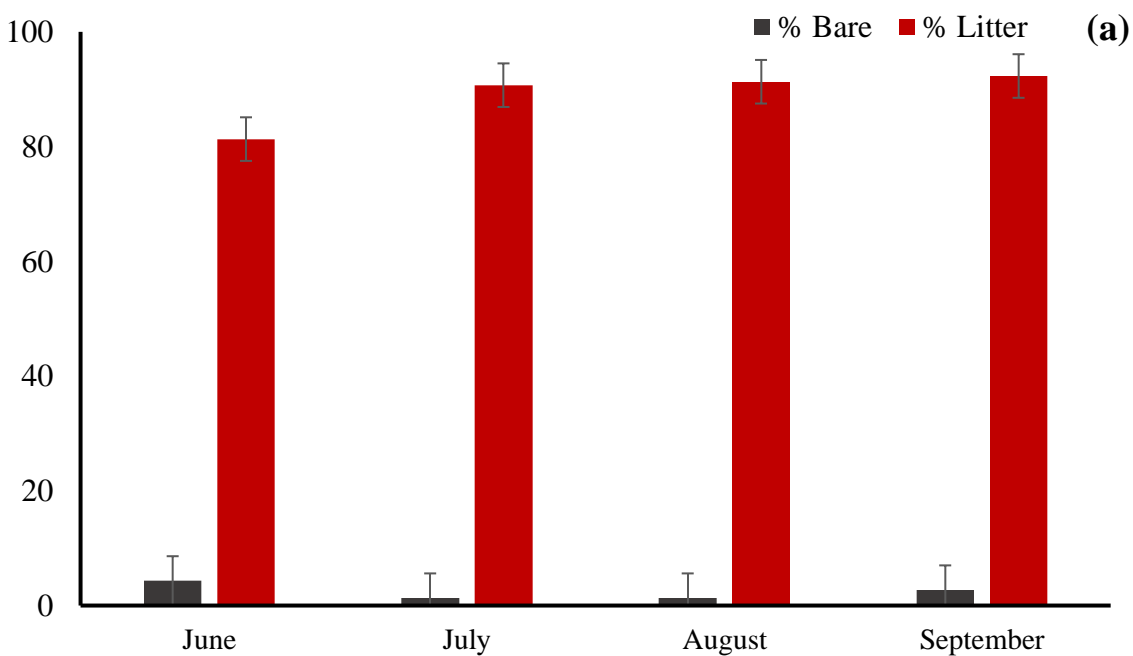


Figure 6. Experimental layout at the University of Nebraska – Lincoln Eastern Nebraska Research and Extension Center at Mead, NE, from 2020-2022. The experiment had a split-plot design with six, 1.20-ha main plots (1-6) and six, 6.70 m² subplots (orange rectangles, not to scale). The main plots consisted of mixed-legume smooth brome grass (*Bromus inermis* Leyss.) pastures and N-fertilized smooth brome grass pastures. The subplots consisted of sod suppression after sorghum × sudangrass interseeding treatments. The subplot treatments were established within one randomly selected paddock (A-F) within each main plot in 2020 and in an adjacent paddock in 2021. The six, 0.20 ha paddocks were used for rotational stocking of 3-4 crossbred steers (*Bos taurus* L.) to maintain even utilization and vegetation heights within and across main plots throughout the study duration.

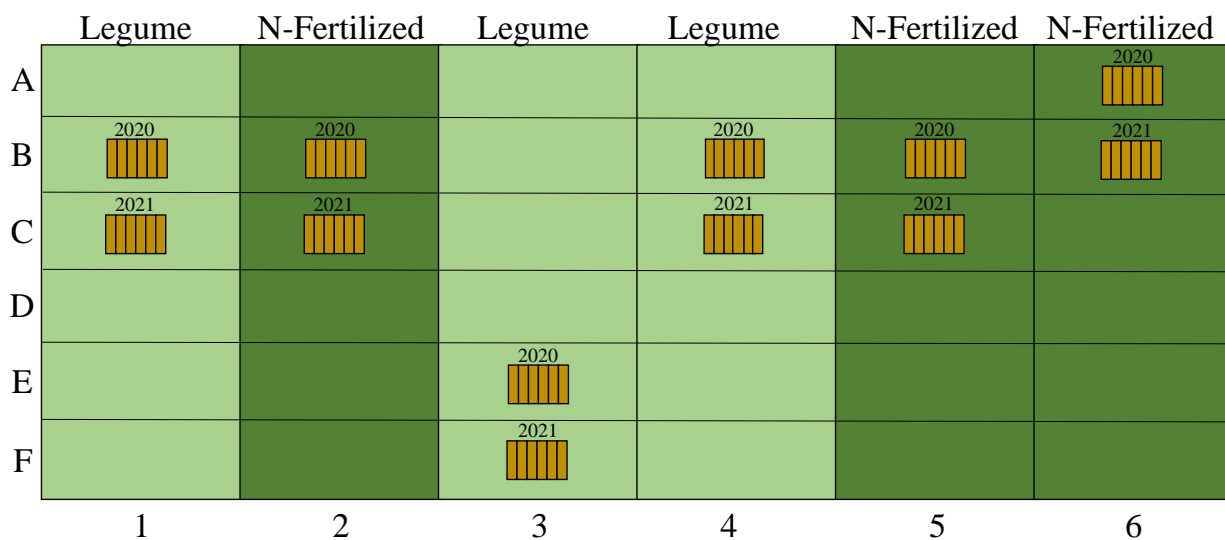


Figure 7. Monthly precipitation during the study years and longer-term average from 1981-2010 at Mead, Nebraska.

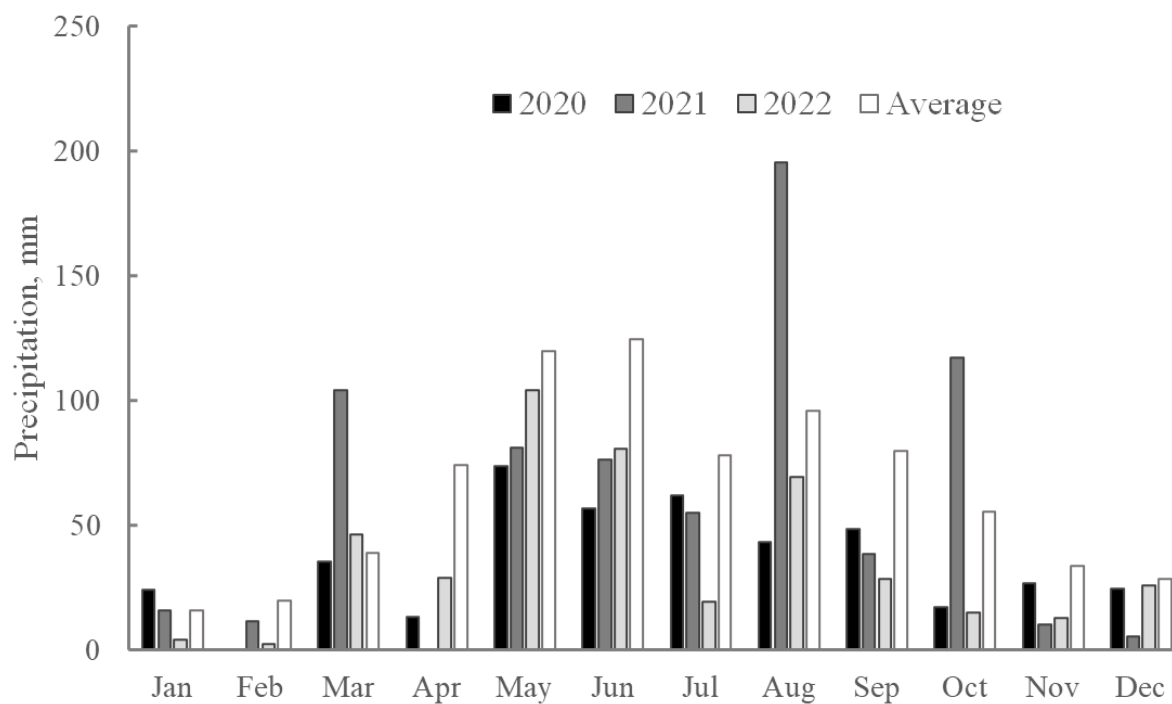


Figure 8. Perennial grass mass in summer as affected by glyphosate rate after interseeding pastures with sorghum × sudangrass at Mead, NE. The summer sampling took place 8 weeks after treatment. Two rotational stocking cycles with cattle grazing preceded the sorghum × sudangrass interseeding and glyphosate applications in spring each year. Each mean \pm SE represents two pasture types and three replicates ($n = 6$).

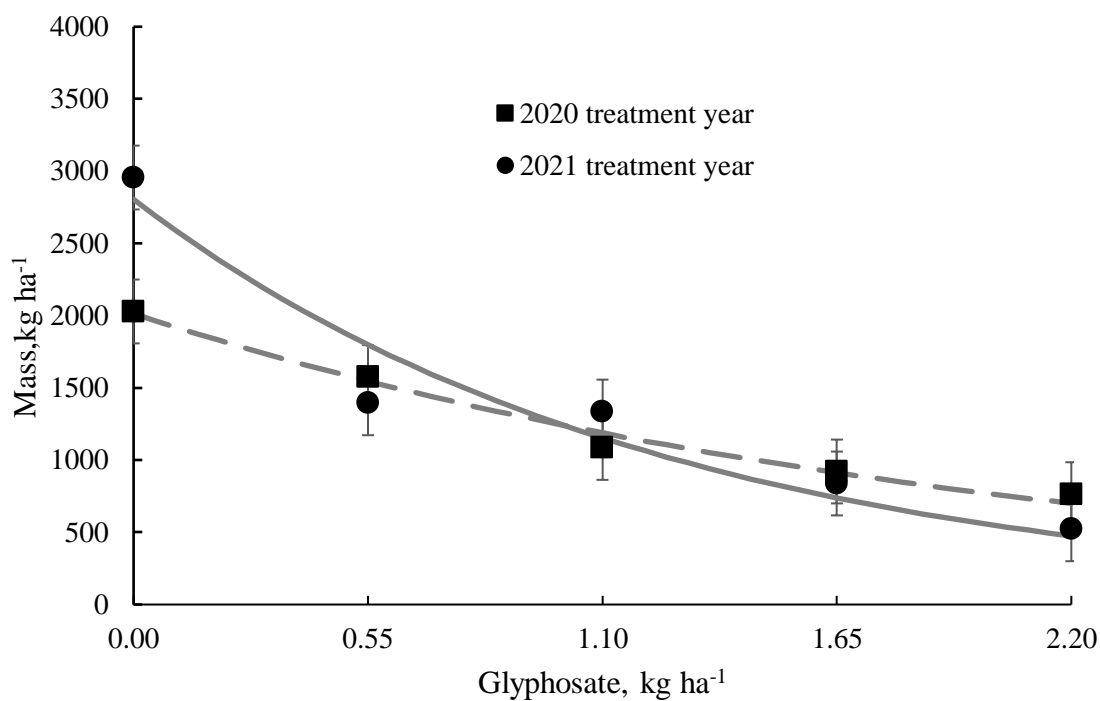


Figure 9. Sorghum \times sudangrass, weedy grass, and total herbage mass in summer as affected by glyphosate rate after interseeding sorghum \times sudangrass into pastures at Mead, NE. The summer sampling time took place 8 weeks after interseeding and sod suppression treatments. Two rotational stocking cycles preceded sorghum \times sudangrass interseeding and the glyphosate treatment applications each year. Each mean \pm SE represents two pasture types, two years, and three replicates ($n = 12$).

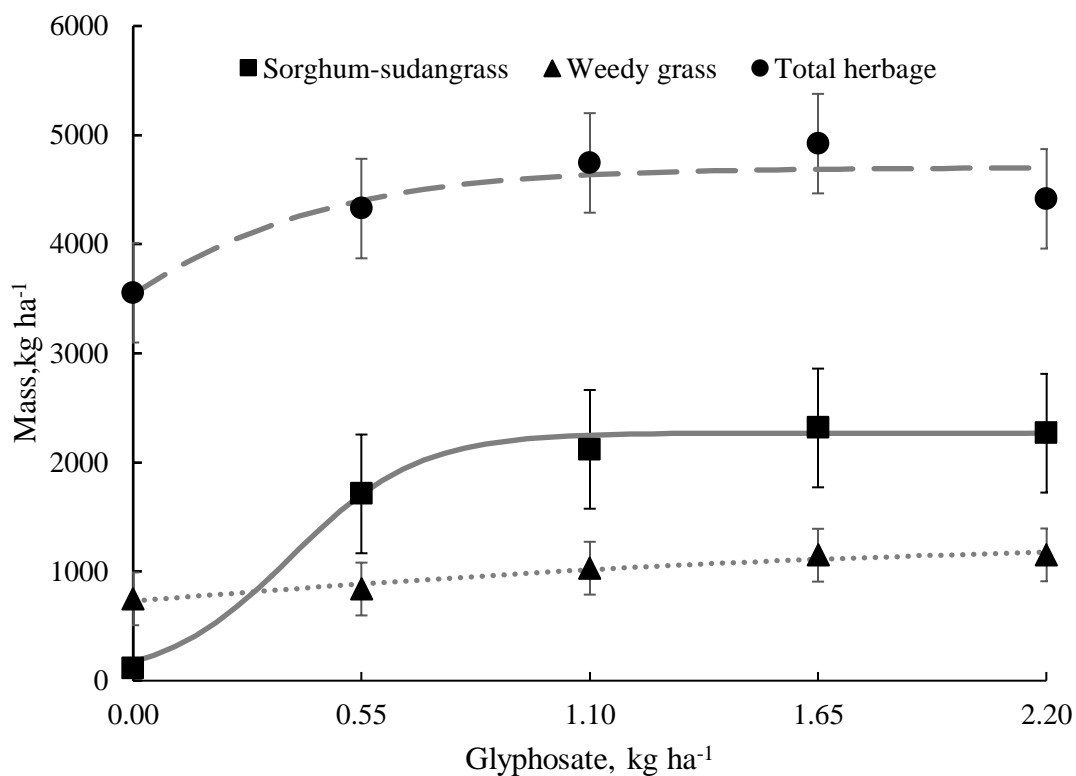
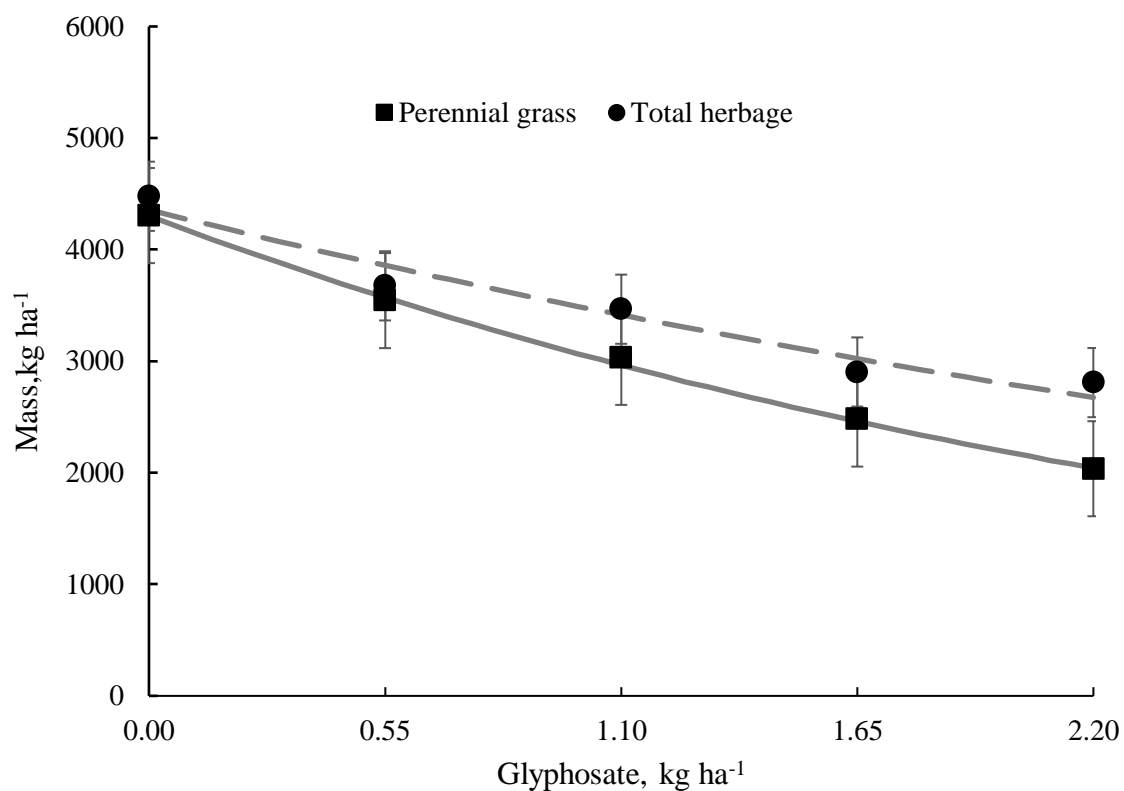


Figure 10. Perennial grass and total herbage mass in the next spring as affected by glyphosate rate after interseeding sorghum × sudangrass the previous spring in pastures at Mead, NE. The next spring sampling time took place 50 weeks after interseeding and sod suppression treatments. Heavy grazing by cattle in two rotational stocking cycles preceded sorghum × sudangrass interseeding and the glyphosate treatment applications the previous spring.



TABLES

Table 1. ANOVA of herbage mass components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions at a double cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.

Effect	Forage species			Weedy species			Total Herbage
	Forage grasses	Legumes	Total	Forbs	Grasses	Total	
P	8.6*	55.6**	5.52	2.9	31.45**	31.92**	10.87*
T	30.61**	149.08**	44.35*	1.31	177.96**	178.31**	123.47**
P × T	10.12*	149.44**	5.13	1.61	9.06*	8.95*	10.35*
Y	36.73**	8.53*	41.54**	0.22	24.23**	24.15**	18.5*
P × Y	4.07	8.62*	3.34	0.35	1.06	1.08	1.82
T × Y	150.98**	8.78*	164.55**	0.49	23.66**	23.55**	106.95**
P × T × Y	20.09*	8.7*	18.94*	0.33	1.06	1.08	13.9*

* $p \leq 0.05$.

** $p \leq 0.01$.

*** $p \leq 0.001$.

Table 2. ANOVA of herbage mass components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions at a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.

Effect	Forage species			Weedy species			Total Herbage
	Forage grasses	Legumes	Total	Forbs	Grasses	Total	
P	6.33	8.58*	5.8	0.27	0.6	0.09	5.01
T	507.54***	3.88	607.51***	4.32	14.21*	5.44	641.83***
P × T	2.51	3.88	1.93	0.04	0.73	0.41	2.55
Y	9.76*	0.81	10.41*	1.44	10.82*	5.17	15.02*
P × Y	0.42	0.81	0.72	1.0	0.57	0.06	0.7
T × Y	241.53***	1.4	275.24***	0.02	10.82*	7.82*	323.99***
P × T × Y	0.83	1.4	1.38	3.13	0.57	1.73	0.9

* $p \leq 0.05$.

** $p \leq 0.01$.

*** $p \leq 0.001$.

Table 3. ANOVA of N concentrations in herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions at a double-cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.

Effect	Forage		Forage species	Weedy species	Total Herbage
	grasses	Legumes			
P	12.34**		3.81#	18.8*	8.72*
T	22.77**		9.6*		8.87*
P × T	0.11		1.03		0
Y	10.42*	0.01	4.68#	1.1	4#
P × Y	0.32		2.56	0.01	0.03
T × Y	0.44		2.83		2.89
P × T × Y	0.07		0.58		0.36

Note: The absence of data indicates that effects and interactions of those variables were not evaluated. Time effects and their interactions were not evaluated for weedy species and legumes due to insufficient plant material available for analysis. Pasture type effects and their interactions were not evaluated for legumes because legumes were not present during the spring sampling time.

* $p \leq 0.05$.

** $p \leq 0.01$.

*** $p \leq 0.001$.

Table 4. ANOVA of N concentrations in herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions in a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.

Effect	Forage		Forage species	Weedy species	Total Herbage
	grasses	Legumes			
P	59.39***		41**		61.21
T	1155.52***	63.52**	635.4***		781.9
P × T	11.51**		1.18		0.6
Y	16.21**	4.42	9.44*		7.94*
P × Y	3.11		0.97		0.61
T × Y	244.15***	3.16	184.96***		163.92***
P × T × Y	2.31		0.56		0.25

Note: The absence of data indicates that effects and interactions of those variables were not evaluated. All effects of weedy species were not evaluated due to insufficient material for analysis. Pasture type effects and their interactions of legumes were not evaluated due to insufficient material for analysis within the N fertilized treatment.

* $p \leq 0.05$.

** $p \leq 0.01$.

*** $p \leq 0.001$.

Table 5. ANOVA of N yields of herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions at a double-cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.

Effect	Forage		Forage species	Weedy species	Total Herbage
	grasses	Legumes			
P	52.58***		36.28**	22.1**	72.04***
T	4.3#	37.78**	15.25**	89.15***	78.79***
P × T	13.95**		5.2#	22.1**	22.6**
Y	31.65**	26.53**	34.52**	28.32**	17.12**
P × Y	10.75*		8.03*	8.31*	3.67#
T × Y	143.76***	26.53**	146.4***	28.32**	98.03***
P × T × Y	43.8**		37.21**	8.31*	24.43**

Note: The absence of data indicates that effects and interactions of those variables were not evaluated. Pasture type effects and their interactions were not evaluated due to insufficient material for analysis in N fertilized treatments.

#p > 0.05.

*p ≤ 0.05.

**p ≤ 0.01.

***p ≤ 0.001.

Table 6. ANOVA of N yields of herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions at a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.

Effect	Forage		Forage species	Weedy species	Total Herbage
	grasses	Legumes			
P	35.86**		39.32**	0.2	45.9***
T	82.86***	1.34	138.68***	2.82	150.57***
P × T	4.19#		4.66#	0.5	5.95*
Y	98.14***	1.42	86.22***	4.74#	93.77***
P × Y	2.78		3.2	0.02	3.1
T × Y	88.99***	2.81	76.7***	7.61*	85.81***
P × T × Y	2.71		3.41	1.04	2.73

Note: The absence of data indicates that effects and interactions of those variables were not evaluated. Pasture type effects and their interactions were not evaluated due to insufficient material for analysis in N fertilized treatments.

#p > 0.05.

*p ≤ 0.05.

**p ≤ 0.01.

***p ≤ 0.001.

Table 7. ANOVA of NDF concentrations in herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions in a double-cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.

Effect	Forage		Forage species	Weedy species	Total Herbage
	grasses	Legumes			
P	0.45		3.49	5.67#	0.15
T	66.87**	26751***	15.40*	35312***	39.55**
P × T	0.78		13.52*	7.82*	6.58#
Y	0.81	27.21*	0.31	2.24	0.46
P × Y	0.13		0.99	0.04	0.01
T × Y	29.76**	27.21*	34.18**	2.24	29.77**
P × T × Y	5.36#		0.43	0.04	4.45

Note: The absence of data indicates that effects and interactions of those variables were not evaluated. Pasture type effects and their interactions were not evaluated due to insufficient material for analysis in N fertilized treatments.

#p > 0.05.

*p ≤ 0.05.

**p ≤ 0.01.

***p ≤ 0.001.

Table 8. ANOVA of NDF concentrations in herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions in a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.

Effect	Forage		Forage species	Weedy species	Total Herbage
	grasses	Legumes			
P	5.55#		0.32	0.03	0.74
T	166.63***	0.59	119.03**	3.15	126.01**
P × T	1.73		1.38	0.24	2.91
Y	51.91**	2.96	42.85**	0.44	29.94**
P × Y	0.02		0.14	0.45	0.2
T × Y	228.13***	1.62	194.66**	1.31	157.04**
P × T × Y	0.03		2.02	1.12	0.2

Note: The absence of data indicates that effects and interactions of those variables were not evaluated. Pasture type effects and their interactions were not evaluated due to insufficient material for analysis in N fertilized treatments.

#p > 0.05.

*p ≤ 0.05.

**p ≤ 0.01.

***p ≤ 0.001.

Table 9. ANOVA of IVOMD concentrations in herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions in a double-cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.

Effect	Forage		Forage species	Weedy species	Total Herbage
	grasses	Legumes			
P	0.05		0.68	4.48	0.07
T	3.84	6291***	0.30	18226***	5.46#
P × T	19.87*		9.89*	4.31	21.44**
Y	0.35	0.36	2.36	48.59**	14.38*
P × Y	0.02		1.09	1.44	0.00
T × Y	118.32**	0.36	109.73**	48.59**	105.2***
P × T × Y	10.14*		9.91*	1.44	13.24*

Note: The absence of data indicates that effects and interactions of those variables were not evaluated. Pasture type effects and their interactions were not evaluated due to insufficient material for analysis in N fertilized treatments.

#p > 0.05.

*p ≤ 0.05.

**p ≤ 0.01.

***p ≤ 0.001.

Table 10. ANOVA of IVOMD concentrations in herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions in a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.

Effect	Forage		Forage species	Weedy species	Total Herbage
	grasses	Legumes			
P	0.04		1.15	0.08	0.26
T	146.71**	.71	108.66**	3.62	113.13**
P × T	1.51		0.67	1.12	0.13
Y	39.45**	7.58	32.32**	0	27.97**
P × Y	4.05		1.7	0.22	1.74
T × Y	15.84*	0.15	9.59*	0.09	7.92#
P × T × Y	4.59#		4.26	1.28	4.32

Note: The absence of data indicates that effects and interactions of those variables were not evaluated. Pasture type effects and their interactions were not evaluated due to insufficient material for analysis in N fertilized treatments.

#p > 0.05.

*p ≤ 0.05.

**p ≤ 0.01.

***p ≤ 0.001.

Table 11. ANOVA of IVOMD yields of herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions at a double-cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.

Effect	Forage		Forage species	Weedy species	Total Herbage
	grasses	Legumes			
P	6.83#		4.21	26.08**	8.61*
T	29.96**	137.32**	42.83**	170.09**	108.2***
P × T	6.93#		3.03	7.69#	6.38#
Y	35.64**	7.42	39.97**	28.52**	14.96*
P × Y	2.41		1.87	1.4	0.68*
T × Y	132.69**	7.42	143.86***	28.52**	80.80***
P × T × Y	15.07*		14.03*	1.4	8.85*

Note: The absence of data indicates that effects and interactions of those variables were not evaluated. Pasture type effects and their interactions were not evaluated due to insufficient material for analysis in N fertilized treatments.

#p > 0.05.

*p ≤ 0.05.

**p ≤ 0.01.

***p ≤ 0.001.

Table 12. ANOVA of IVOMD yields of herbage components including forage species: forage grasses, legumes, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (P), time (T), year (Y), and their interactions in a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.

Effect	Forage		Forage species	Weedy species	Total Herbage
	grasses	Legumes			
P	6.67#		6.6#	0.43	5.49#
T	497.66***	0.58	650.24***	4.09	632.98***
P × T	1.91		1.92	0.11	2.8
Y	10.68*	2.83	10.96*	3.42	16.19*
P × Y	0.18		0.78	0.07	0.62
T × Y	298.98***	0.16	381.47***	4.51	422.42***
P × T × Y	0.53		0.84	0.41	0.34

Note: The absence of data indicates that effects and interactions of those variables were not evaluated. Pasture type effects and their interactions were not evaluated due to insufficient material for analysis in N fertilized treatments.

#p > 0.05.

*p ≤ 0.05.

**p ≤ 0.01.

***p ≤ 0.001.

Table 13. ANOVA of bare ground and litter count data as affected by pasture type (P), time (T), year (Y), and their interactions in a double-cropped annual forage system (DCAFS) near Mead, Nebraska from 2022-2023.

Effect	Bare	
	ground	Litter
P	4.67#	2.23
T	1.4	1.1
P × T	0.2	0.4
Y	40.6***	15.29**
P × Y	0.4	0.34
T × Y	10.82***	9.98**
P × T × Y	1.6	1.55

$p > 0.05$. * $p \leq 0.05$. ** $p \leq 0.01$. *** $p \leq 0.001$.

Table 14. ANOVA of bare ground and litter count data as affected by pasture type (P), time (T), year (Y), and their interactions in a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.

Effect	Bare	
	ground	Litter
P	2.77	3.04
T	1.12	6.71
P × T	1.48	0.22
Y	0.38	3.12
P × Y	0.12	0.09
T × Y	6.32**	7.71**
P × T × Y	0.23	0.97

* $p \leq 0.05$. ** $p \leq 0.01$. *** $p \leq 0.001$.

Table 15. ANOVA of steer initial body weights, final body weights, average daily body weight gains, and total body weight gains as affected by pasture type (P), year (Y), and their interactions in a diverse perennial circular forage system (DPCFS) near Mead, Nebraska from 2022-2023.

Effect				Total
	Initial BW	Final BW	ADG	gains
P	0.25	0.91	0.76	0.87
Y	2586.75***	3.33	37.19**	34.19**
P × Y	3.48#	0.02	0.02	0.02

$p > 0.05$. * $p \leq 0.05$. ** $p \leq 0.01$. *** $p \leq 0.001$.

Table 16. Forage grass, legume, forage species, and total herbage mass in the double-cropped annual forage system (DCAFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean.

Year	Herbage component	Pasture type	Sampling time		P value
			Spring DM, kg ha ⁻¹	Summer DM, kg ha ⁻¹	
2022	Forage grass	FERT	5880	2021	*
		LEG	4036	1425	#
		P value	NS	NS	
	Legume	FERT	/	/	
		LEG	2	706	**
		P value			
	Forage species	FERT	5881	2021	*
		LEG	4038	2131	NS
		P value	NS	NS	
Herbage	FERT	5892	6020	NS	
	LEG	4049	4684	NS	
	P value	NS	NS		
2023	Forage grass	FERT	1717	13922	**
		LEG	2234	7099	**
		P value	NS	**	
	Legume	FERT	/	/	
		LEG	0	1153	***
		P value			
	Forage species	FERT	1717	13922	**
		LEG	2234	8252	**
		P value	NS	**	
Herbage	FERT	1717	15796	***	
	LEG	2234	9426	**	
	P value	NS	**		

Table 17. Weedy grass and weedy species mass at the double-cropped annual forage system grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer). Weedy grasses included barnyardgrass, yellow foxtail, giant foxtail, and crabgrass and weedy species included weedy grasses and other forbs including prostrate knotweed, mares tail, and velvetleaf.

Herbage component	Pasture type	Sampling time		P value
		Spring DM, kg ha ⁻¹	Summer DM, kg ha ⁻¹	
Weedy Grass	FERT	5	2937	**
	LEG	5	1858	**
	P value	NS	**	
Weedy Species	FERT	5	2937	**
	LEG	6	1864	**
	P value	NS	**	

Table 18. Weedy grass and weedy species mass at the double-cropped annual forage system grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer). Weedy grasses included barnyardgrass, yellow foxtail, giant foxtail, and crabgrass and weedy species included weedy grasses and other forbs including prostrate knotweed, mares tail, and velvetleaf.

Herbage Component	Year	Sampling time		P value
		Spring DM, kg ha ⁻¹	Summer DM, kg ha ⁻¹	
Weedy Grass	2022	10	3275	**
	2023	0	1520	**
	P value	NS	**	
Weedy Species	2022	11	3277	**
	2023	0	1525	**
	P value	NS	**	

Table 19. Forage grass, forage species, weedy grass, weedy species, and total herbage mass in the diverse perennial circular forage system (DPCFS) grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover. Weedy grass species was dominated by yellow foxtail and weedy species consisted of weedy grasses and the weedy forbs wild mustard, field bindweed, and horsenettle.

Herbage Component	Year	Sampling time		P value
		Spring DM, kg ha ⁻¹	Summer DM, kg ha ⁻¹	
Forage Grass	2022	8054	875	***
	2023	5713	4395	**
	P value	**	**	
Forage Species	2022	8180	979	***
	2023	5847	4439	**
	P value	**	**	
Weedy Grass	2022	0	14	NS
	2023	0	212	**
	P value	NS	**	
Weedy Species	2022	51	34	NS
	2023	32	217	*
	P value	NS	*	
Herbage	2022	8231	1012	***
	2023	5878	4656	**
	P value	**	***	

Table 20. Forage grass, legume, forage species, and total herbage N concentrations in the double-cropped annual forage system (DCAFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types; at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean; and in the sampling years 2022 and 2023. Weedy species included barnyardgrass, yellow foxtail, giant foxtail, crabgrass, prostrate knotweed, mares tail, and velvetleaf.

Herbage component	Pasture type	N, g kg⁻¹	Sampling time	N, g kg⁻¹	Year	N, g kg⁻¹
Forage Grass	FERT	13.94	Spring	14.72	2022	10.50
	LEG	9.58	Summer	8.80	2023	13.02
	P value	**		**		*
Legume	FERT		Spring		2022	20.07
	LEG	19.99	Summer	19.99	2023	19.92
	P value					NS
Forage Species	FERT	13.95	Spring	14.72	2022	11.78
	LEG	11.34	Summer	10.58	2023	13.51
	P value	#		*		*
Weedy Species	FERT	14.70	Spring		2022	10.43
	LEG	7.74	Summer	11.22	2023	12.02
	P value	*				NS
Herbage	FERT	14.69	Spring	14.71	2022	11.89
	LEG	10.76	Summer	10.74	2023	13.56
	P value	*		*		#

Table 21. Forage grass, legume, forage species, weedy species, and total herbage N yields in the double-cropped annual forage system (DCAFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean. Weedy species included barnyardgrass, yellow foxtail, giant foxtail, crabgrass, prostrate knotweed, mares tail, and velvetleaf.

Year	Herbage component	Pasture type	Sampling time		P value
			Spring N, kg ha ⁻¹	Summer N, kg ha ⁻¹	
2022	Forage grass	FERT	86.90	17.27	***
		LEG	47.63	7.93	**
		P value	**	NS	
	Legume	FERT			
		LEG	0	14.45	**
		P value			
	Forage species	FERT	86.90	17.27	***
		LEG	47.63	22.40	*
		P value	***	NS	
	Weedy species	FERT	0	53.68	***
		LEG	0	17.53	**
		P value	NS	***	
Herbage	FERT	86.9	70.98	NS	
	LEG	47.60	39.90	NS	
	P value	**	*		
2023	Forage grass	FERT	32.80	170.67	***
		LEG	30.77	50.97	#
		P value	NS	***	
	Legume	FERT			
		LEG	0	22.97	**
		P value			
	Forage species	FERT	32.80	170.67	***
		LEG	30.77	73.93	**
		P value	NS	***	
	Weedy species	FERT	0	28.93	***
		LEG	0	10.17	*
		P value	NS	**	
Herbage	FERT	32.80	199.60	***	
	LEG	30.77	84.10	**	
	P value	NS	***		

Table 22. Forage grass, forage species, and total herbage N concentrations in the diverse perennial circular forage system (DPCFS) grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover.

Herbage Component	Year	Sampling time		P value
		Spring N, g kg ⁻¹	Summer N, g kg ⁻¹	
Forage Grass	2022	13.66	32.36	***
	2023	19.68	22.06	**
	P value	***	***	
Forage Species	2022	13.93	31.52	***
	2023	19.90	22.07	**
	P value	***	***	
Herbage	2022	13.93	31.23	***
	2023	19.90	21.90	*
	P value	***	***	

Table 23. Forage grass, legume, and forage species N concentrations in the diverse perennial circular forage system (DPCFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover.

Herbage component	Pasture type	Sampling time		P value
		Spring N, g kg ⁻¹	Summer N, g kg ⁻¹	
Forage Grass	FERT	18.38	27.83	***
	LEG	14.95	26.50	***
	P value	***	*	
Legume	FERT			
	LEG	26.67	22.27	**
	P value			
Forage Species	FERT	18.38	27.83	***
	LEG	15.45	25.75	***
	P value	**	**	

Table 24. Forage grass, forage species, weedy species, and total herbage N yields in the diverse perennial circular forage system (DPCFS) grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover. Weedy species consisted of yellow foxtail, wild mustard, field bindweed, and horsenettle.

Herbage Component	Year	Sampling time		P value
		Spring N, kg ha ⁻¹	Summer N, kg ha ⁻¹	
Forage Grass	2022	111.33	28.17	***
	2023	113.03	97.72	*
	P value	NS	***	
Forage Species	2022	114.68	30.80	***
	2023	116.67	98.60	**
	P value	NS	***	
Weedy Species	2022	1.14	0.46	NS
	2023	0.73	3.90	**
	P value	NS	**	
Total Herbage	2022	115.84	31.28	***
	2023	117.42	102.47	*
	P value	NS	***	

Table 25. Forage grass, forage species, and total herbage N yields in the diverse perennial circular forage system (DPCFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover.

Herbage component	Pasture type	Sampling time		P value
		Spring N, kg ha ⁻¹	Summer N, kg ha ⁻¹	
Forage Grass	FERT	133.92	73.60	***
	LEG	90.45	52.28	**
	P value	**	*	
Forage Species	FERT	133.92	73.60	***
	LEG	97.43	55.80	***
	P value	**	*	
Herbage	FERT	135.31	75.66	***
	LEG	97.95	58.08	***
	P value	**	*	

Table 26. Forage grass, forage species, weedy species, and total herbage NDF concentrations in the double-cropped annual forage system (DCAFS) grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean. Weedy species included barnyardgrass, yellow foxtail, giant foxtail, crabgrass, prostrate knotweed, mares tail, and velvetleaf.

Herbage Component	Year	Sampling time		P value
		Spring NDF, g kg ⁻¹	Summer NDF, g kg ⁻¹	
Forage Grass	2022	602.7	617.0	NS
	2023	569.4	640.9	**
	P value	*	*	
Forage Species	2022	602.4	590.4	NS
	2023	569.4	630.5	**
	P value	*	*	
Weedy Species	2022	/	617.2	
	2023	/	627.1	
	P value		NS	
Herbage	2022	601.2	605.6	NS
	2023	569.4	630.4	**
	P value	*	*	

Table 27. Forage grass, legume, forage species, weedy species, and total herbage NDF concentrations in the double-cropped annual forage system (DCAFS) grazing enclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean. Weedy species included barnyardgrass, yellow foxtail, giant foxtail, crabgrass, prostrate knotweed, mares tail, and velvetleaf.

Herbage component	Pasture type	Sampling time		P value
		Spring NDF, g kg ⁻¹	Summer NDF, g kg ⁻¹	
Forage Grass	FERT	580.8	628.3	**
	LEG	591.2	629.5	**
	P value	NS	NS	
Legume	FERT			
	LEG	/	404.5	
	P value			
Forage Species	FERT	580.7	628.3	**
	LEG	591.1	592.6	NS
	P value	NS	*	
Weedy Species	FERT	/	612.9	
	LEG	/	631.4	
	P value		*	
Herbage	FERT	580.3	626.3	**
	LEG	590.3	609.7	#
	P value	NS	*	

Table 28. Forage grass, forage species, weedy species, and total herbage NDF concentrations in the diverse perennial circular forage system (DPCFS) grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth bromegrass and the legumes birdsfoot trefoil, alfalfa, and red clover. Weedy species consisted of yellow foxtail, wild mustard, field bindweed, and horsenettle.

Herbage Component	Year	Sampling time		P value
		Spring NDF, g kg ⁻¹	Summer NDF, g kg ⁻¹	
Forage Grass	2022	656.7	506.0	***
	2023	614.2	626.0	NS
	P value	**	***	
Forage Species	2022	652.7	493.4	***
	2023	605.3	624.7	#
	P value	**	***	
Weedy Species	2022	255.6	323.5	NS
	2023	60.5	375.3	NS
	P value	NS	NS	
Herbage	2022	651.7	489.9	***
	2023	603.6	612.5	NS
	P value	**	**	

Table 29. Forage grass, forage species, weedy species, and total herbage NDF concentrations in the diverse perennial circular forage system (DPCFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome grass and the legumes birdsfoot trefoil, alfalfa, and red clover. Weedy species consisted of yellow foxtail, wild mustard, field bindweed, and horsenettle.

Herbage component	Pasture type	Sampling time		P value
		Spring NDF, g kg ⁻¹	Summer NDF, g kg ⁻¹	
Forage Grass	FERT	626.6	564.2	**
	LEG	644.4	567.9	**
	P value	#	NS	
Legume	FERT			
	LEG	289.5	362.3	NS
	P value			
Forage Species	FERT	626.6	564.2	**
	LEG	631.4	554.0	**
	P value	NS	NS	
Weedy Species	FERT	125.3	369.9	NS
	LEG	190.7	328.9	NS
	P value	NS	NS	
Herbage	FERT	624.6	559.8	**
	LEG	630.7	542.6	**
	P value	NS	NS	

Table 30. Forage grass, legume, forage species, weedy species, and total herbage IVOMD concentrations in the double-cropped annual forage system (DCAFS) grazing exclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean. Weedy species included barnyardgrass, yellow foxtail, giant foxtail, crabgrass, prostrate knotweed, mares tail, and velvetleaf.

Year	Herbage component	Pasture type	Sampling time		P value
			Spring IVOMD, g kg ⁻¹	Summer IVOMD, g kg ⁻¹	
2022	Forage grass	FERT	597.9	673.1	**
		LEG	590.5	682.2	**
		P value	NS	NS	
	Legume	FERT			
		LEG	/	594.6	
		P value			
	Forage species	FERT	597.8	673.1	**
		LEG	590.1	652.1	**
		P value	NS	NS	
	Weedy species	FERT	/	614.6	
		LEG	/	622.2	
		P value		NS	
	Herbage	FERT	596.8	634.3	*
		LEG	588.7	636.9	*
		P value	NS	NS	
2023	Forage grass	FERT	692.3	584.7	**
		LEG	645.2	636.9	NS
		P value	*	*	
	Legume	FERT			
		LEG	/	585.7	
		P value			
	Forage species	FERT	692.3	584.7	**
		LEG	645.2	629.2	NS
		P value	NS	NS	
	Weedy species	FERT	/	543.4	
		LEG	/	622.2	
		P value		**	
	Herbage	FERT	692.3	579.4	**
		LEG	645.2	621.8	NS
		P value	*	*	

Table 31. Forage grass, legume, forage species, weedy species, and total herbage IVOMD yields in the double-cropped annual forage system (DCAFS) grazing enclosures within N fertilized grass (FERT) and mixed grass-legume (LEG) pasture types. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where spring growth consisted of the forage grass triticale and the legume red clover and in the summer, the forage grass was pearl millet and the legume was forage soybean. Weedy species included barnyardgrass, yellow foxtail, giant foxtail, crabgrass, prostrate knotweed, mares tail, and velvetleaf.

Year	Herbage component	Pasture type	Sampling time		P value
			Spring IVOMD, kg ha ⁻¹	Summer IVOMD, kg ha ⁻¹	
2022	Forage grass	FERT	3515	1363	*
		LEG	2388	973	#
		P value	NS	NS	
	Legume	FERT			
		LEG	0	422	*
		P value			
	Forage species	FERT	3515	1363	*
		LEG	2388	1337	NS
		P value	NS	NS	
	Weedy species	FERT	0	2460	**
		LEG	0	1589	**
		P value		*	
	Herbage	FERT	3515	3823	NS
		LEG	2388	2925	NS
		P value	NS	NS	
2023	Forage grass	FERT	1191	8124	**
		LEG	1438	4528	**
		P value	NS	**	
	Legume	FERT			
		LEG	0	676	**
		P value			
	Forage species	FERT	1191	8124	**
		LEG	1438	5205	**
		P value	NS	*	
	Weedy species	FERT	0	1023	**
		LEG	0	673	*
		P value		NS	
	Herbage	FERT	1191	9147	**
		LEG	1438	5878	**
		P value	NS	**	

Table 32. Forage grass, forage species, weedy species, and total herbage IVOMD concentrations in the diverse perennial circular forage system (DPCFS) grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth bromegrass and the legumes birdsfoot trefoil, alfalfa, and red clover. Weedy species consisted of yellow foxtail, wild mustard, field bindweed, and horsenettle.

Herbage Component	Year	Sampling time		P value
		Spring IVOMD, g kg ⁻¹	Summer IVOMD, g kg ⁻¹	
Forage Grass	2022	544.7	642.7	**
	2023	530.6	580.2	**
	P value	NS	**	
Forage Species	2022	545.0	642.7	**
	2023	526.2	579.2	**
	P value	NS	**	
Weedy Species	2022	248.5	482.7	NS
	2023	211.8	532.6	NS
	P value	NS	NS	
Herbage	2022	544.6	643.2	**
	2023	526.5	583.8	*
	P value	NS	*	

Table 33. Forage grass, forage species, weedy species, and total herbage IVOMD yields in the diverse perennial circular forage system (DPCFS) grazing exclosures. Sampling took place during 2022 and 2023 at two times including mid-June (Spring) and early September (Summer) where growth consisted of the forage grass smooth brome and the legumes birdsfoot trefoil, alfalfa, and red clover. Weedy species consisted of yellow foxtail, wild mustard, field bindweed, and horsenettle.

Herbage Component	Year	Sampling time		P value
		Spring IVOMD, kg ha ⁻¹	Summer IVOMD, kg ha ⁻¹	
Forage Grass	2022	4381	564	***
	2023	3029	2546	*
	P value	**	***	
Forage Species	2022	4452	628	***
	2023	3075	2568	*
	P value	**	***	
Weedy Species	2022	24.5	22.3	NS
	2023	18.4	110	#
	P value	NS	#	
Herbage	2022	4477	651	***
	2023	3093	2708	#
	P value	**	**	

Table 34. ANOVA of herbage mass components including forage species: perennial grasses, legumes, sorghum × sudangrass, and total forage species; weedy species: forbs, grasses, and total weedy species; and total herbage as affected by pasture type (T), sod suppression (S) after interseeding, sampling date (D) after sod suppression, sod suppression after interseeding year (Y), and their interactions at Mead, Nebraska from 2020-2022.

Sampling time	Effect	Sorghum						
		Perennial grasses	Legumes	× sudangrass	Weedy Forbs	Weedy Grasses	Total	Total herbage
Summer	T	1.3		0.6	0.1	1.5	0.0	0.3
	S	22.0***	2.8*	3.5**	1.2	2.6*	5.3***	2.5*
	T × S	2.0		0.3	0.3	1.0	0.6	0.5
	Y	4.6*	1.6	0.9	6.0*	3.6#	17.7***	11.7**
	T × Y	0.2		0.1	0.0	0.1	1.2	0.4
	S × Y	3.0*	0.5	0.7	1.1	0.4	1.1	1.2
	T × S × Y	0.2		0.4	0.3	0.8	0.5	0.6
Next Spring	T	10.1**			3.6#	2.6	0.0	1.9
	S	7.3***	1.8		1.8	2.5*	5.3***	3.8**
	T × S	0.1			0.5	2.7*	0.6	0.4
	Y	20.1**	2.2		7.8**	4.7*	17.7***	8.6**
	T × Y	1.1			2.3	2.6	1.2	2.9
	S × Y	0.4	1.8		1.4	2.5*	1.1	0.7
	T × S × Y	0.3			0.3	2.7*	0.5	0.4

Note: The absence of data indicates that effects and interactions of those variables were not evaluated.

$p > 0.05 - 0.10$

* $p \leq 0.05$.

** $p \leq 0.01$.

*** $p \leq 0.001$.

Table 35. Perennial grass, total forage species, and total herbage mass in pastures at Mead, NE relative to sampling date after interseeding × interseeding year interactions. The summer sampling took place 8 weeks after interseeding and application of sod suppression treatments while the next spring sampling date took place 50 weeks after interseeding and sod suppression.

Herbage component	Treatment year	Sampling time	
		Summer	Next spring
Perennial grass	2020	1355	3700
	2021	1630	2597
		*	***
Weedy forb	2020	21	53
	2021	364	462
		*	**
Weedy grass	2020	644	0
	2021	1024	2
		#	*
Total	2020	3515	3854
	2021	4801	3115
		**	**

Note:

$p \leq 0.10$

* $p \leq 0.05$.

** $p \leq 0.01$.

*** $p \leq 0.001$.