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Herbage mass responses to sod suppression with glyphosate in pastures interseeded with sorghum × sudangrass

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Abstract

Interseeding annual warm-season forages into perennial cool-season grasses may increase herbage mass and quality. Yet, methods to do so successfully remain elusive. From 2020 to 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 mixed-legume smooth bromegrass (*Bromus inermis* Leyss.) pastures. Sod suppression treatments included glyphosate [N-(phosphonomethyl) glycine] applications of 0, 0.55, 1.10, 1.65, and 2.20 kg ha^{-1} on pastures that were heavily grazed in 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 2316 kg ha^{-1} as glyphosate rate increased to 1.65 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 indicated the presence of a 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.

1 | INTRODUCTION

Every grassland biome experiences periods when forage growth diminishes due to abiotic factors impacting photosynthetic capacity. A community dominated by warm-season plants with a C_4 photosynthetic mechanism will have reduced production during colder conditions (Yamori et al., 2014), whereas a cool-season crop with a C_3 photosynthetic mechanism will experience its production shortage when conditions are hot, dry, and of high light intensity (Ehleringer & 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 & Perry, 1990; Ottman & Mostafa, 2014).

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To sustain high forage production during the summer slump, forage systems benefit from having a C_4 component in addition to the C_3 forage base. For example, 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 (Mercier et al., 2021; Venuto & Kindiger, 2008) and nutritive value (Beck et al., 2007; Pedersen & Toy, 1997) when perennial cool-season grasses like smooth bromegrass (*Bromus inermis* Leyss.) experience reduced growth (Collins & Casler, 1990; Jensen et al., 2002; Moyer & Sweeney, 2016). Additionally, these two species exhibit growth complementarity because C_3 optimum growth occurs between 20 and 25°C while optimum C_4 growth occurs between 38 and 45°C (Sage, 2002).

Including annual warm-season grass 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 perennial cool-season grass pastures. This has been a successful method in previous research, significantly increasing forage accumulation during the summer slump (Belesky et al., 1981; Hart et al., 1971). Sod-seeding is a concept which intends to introduce or add species to a system through direct seeding into established pastures and rangelands without tillage (Koch et al., 1983). Indeed, 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 grass pastures under mowing regimes with successful annual warm-season grass sod-seedings (Clapham et al., 2011; Guretzky et al., 2020; Harmoney & 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 perennial cool-season grass pastures where grazing is the mode of sod suppression. Guretzky et al. (2023) 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 annual warm-season grass 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 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; Bush et al., 1989; Samson & Moser, 1982), but not in an application coupled with grazing.

One of the most common chemicals that has been tested for use as a sod-suppressant is glyphosate [N-(phosphonomethyl) glycine]. At rates of 1.1 kg ha^{-1}, glyphosate has been shown to suppress resident smooth bromegrass growth into late summer without a total kill (Samson & 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 & Kirby, 1991). In a warm-season perennial planting and sod suppression study, glyphosate application 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 <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 bromegrass sods following heavy grazing to accommodate sod-seeded sorghum × sudangrass emergence and summer growth. If establishment was achieved, we also wanted to determine how glyphosate application rates affected recovery of smooth bromegrass the next spring to maintain as much perennial forage as possible.

Core Ideas

- Interseeding pastures with annual warm-season forages may increase forage accumulation and nutritive value.
- The best practice has been to interseed after stockpiling, mowing, and removing existing herbage in spring.
- The use of glyphosate coupled with heavy grazing in spring for sod suppression has not been evaluated.
- Sorghum × sudangrass, weedy grass, and total herbage mass showed logistic growth with an increasing glyphosate rate.
- Reduced perennial grass mass the next spring indicated pastures did not recover from glyphosate application.

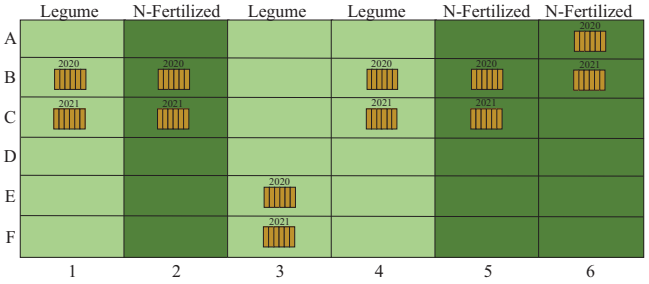


FIGURE 1 Experimental layout at the University of Nebraska Eastern Nebraska Research, Extension and Education Center near Mead, NE, from 2020 to 2022. The experiment had a split-plot design with six, 1.20-ha main plots (1–6) and six, 6.70 m^2 subplots (orange rectangles, not to scale). The main plots consisted of mixed-legume and N-fertilized smooth bromegrass (*Bromus inermis* Leyss.) pastures. The subplots consisted of sod suppression after sorghum × sudangrass [*Sorghum bicolor* (L.) Moench × *S. bicolor* (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan] 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 three to four crossbred steers (*Bos taurus* L.) to maintain even utilization and vegetation heights within and across main plots throughout the study.

2 | MATERIALS AND METHODS

2.1 | Site history

We conducted the research in permanent pasture at the University of Nebraska Eastern Nebraska Research, Extension and Education Center near Mead, Nebraska (Figure 1). The pasture, originally seeded with smooth bromegrass 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, birdsfoot trefoil (*Lotus corniculatus* L.), and red clover (*Trifolium pratense* L.). Of those six, three continued to receive N fertilizer annually in spring, but the three mixed-legume pastures remained unfertilized. From 2012 to 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 to 2019, each of the N-fertilized and mixed-legume 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 to 2022. The site contained about 52% Tomek silt loam soil (fine, smectitic, mesic Pachic Argiudolls) with 0%–2% slopes, 28% Yutan silty clay loam soil (fine-silty, mixed, superactive, mesic Mollic Hapludalfs) with 2%–6% slopes, and 20% Filbert silt loam soil (fine, smectitic, mesic Vertic Argialbolls) with 0%–1% slopes (USDA-NRCS, 2022).

2.2 | Experimental design

The experiment from 2020 to 2022 had a split-plot design with three replications (Figure 1). Main plots consisted of three N-fertilized and three mixed-legume smooth bromegrass pastures. 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, that is, 2.20 kg ha^{-1}, for glyphosate (N-(phosphonomethyl) glycine) in pastures (Samson & 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 exclosure. The subplots had a width of 1.83 m and length of 3.66 m (6.70 m^2) to accommodate the sprayer and pass of a 1.52-m wide Great Plains drill.

2.3 | Stocking cycles, interseeding, and sod suppression

The pastures supported four rotational stocking cycles in 2020 and five rotational 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 April 28, 2020, and May 1, 2021, and the first stocking period in the treatment paddocks lasted 7 days in 2020 and 14 days in 2021. The treatment paddocks had rest periods of 22 days in 2020 and 13 days in 2021, while cattle rotated every 2–4 days among the five nontreatment paddocks in each main plot. On May 26, 2020, and May 27, 2021, the second stocking cycle began in the treatment paddocks, and the stocking period lasted 14 days. Upon rotation of the cattle for the second stocking period in the nontreatment paddocks on June 9, 2020 and June 10, 2021, we interseeded sorghum × sudangrass cv. Super Sugar (Prairie State Seed) at a rate of 42 kg pure live seed ha^{-1} and applied the glyphosate treatments within 48 h to the 6.70-m^2 subplots in the treatment

paddocks (Figure 1). The drill had a 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 N-fertilized main plots, 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 with a rest period of about 8 weeks, skipping those paddocks during the third stocking cycle, while cattle rotated twice, every 6 days through the five nontreatment paddocks. The fourth stocking cycle resumed in the treatment paddocks on August 5, 2020, and August 9, 2021, and the stocking period lasted 6 days. In 2020, the stocking season ended after the fourth stocking cycle in the treatment paddocks because of drought. In 2021, the treatment paddocks had a fifth stocking cycle and 6-day stocking period from September 7 to 13 after cattle had rotated one last time every 5–6 days 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).

2.4 | 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 August 5, 2020 and August 9, 2021 (i.e., 8 weeks after interseeding) and in the next spring on May 26, 2021 and May 27, 2022 (i.e., about 50 weeks after interseeding). During the samplings, we hand clipped a 0.3-m^2 quadrat within each subplot at ground level and sorted the herbage into perennial grasses, legumes, sorghum × sudangrass, weedy forbs, and weedy annual grasses. 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 and total herbage on an area basis.

2.5 | Statistical analysis

We used mixed model and nonlinear regression procedures in SAS version 9.4 for statistical analyses. In initial analyses, we analyzed herbage mass responses by sampling time (i.e., in summer and next spring samplings) with an analysis of variance (ANOVA) model that included main effects and interactions of pasture type, sod suppression after interseeding treatment, and interseeding year. A repeated statement was included specifying interseeding year as a repeated measure, and a subject equal to the replication × pasture type × 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 N-fertilized pastures.

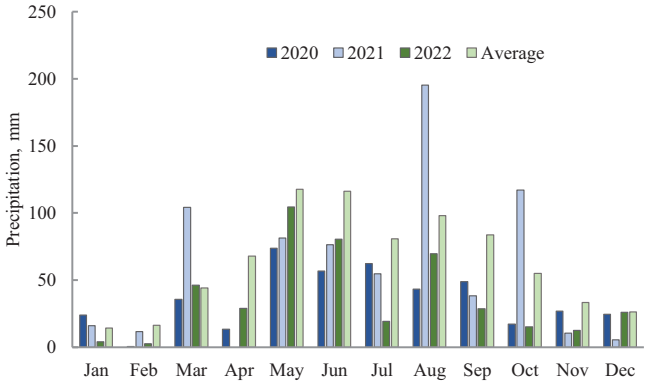


FIGURE 2 Monthly precipitation during the study years and longer term average from 1981 to 2022 near Mead, NE.

3 | RESULTS

3.1 | Weather conditions

The historical average annual precipitation from 1981 to 2022 was 748 mm of rainfall, but during the 3 years of our study, rainfall was down to 427, 711, and 438 mm in 2020, 2021, and 2022, respectively. 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 monthly rainfall accumulation by 136%, 99%, and 112% above the longer term averages (Figure 2). The average annual temperatures for 2020, 2021, and 2022 were 10.4, 10.7, and 9.8°C, respectively, while the longer term average temperature was 10.1°C.

3.2 | Analysis of variance

Pasture type did not influence herbage mass components in the summer sampling after interseeding and sod suppression (Table 1). 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

TABLE 1 Analysis of variance of herbage mass components in summer (i.e., in August 2020 and 2021) and next spring (i.e., in May 2021 and 2022) samplings as affected by pasture type (T), sod suppression after interseeding (S), interseeding year (Y), and their interactions near Mead, NE.

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

Note: The absence of data indicates that effects and interactions of those variables were not evaluated.
#$p > 0.05$–0.10; *$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$.

context of a three-way interaction with sod suppression after interseeding treatment and interseeding year (Table 1). 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 1). Interseeding year also influenced several components in the summer and next spring samplings.

3.3 | Pasture type effects

The N-fertilized and mixed-legume pastures had similar perennial grass mass in the summer sampling after interseeding and sod suppression (1566 and 1419 kg ha^{-1}, respectively; $p = 0.258$), but in the next spring sampling, the N-fertilized pastures had 28% greater perennial grass mass than the 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 the N-fertilized pastures compared to 397 kg ha^{-1} in the mixed-legume pastures in the next spring sampling ($p = 0.062$). It was not affected by pasture type in the summer sampling, averaging 228 and 187 kg ha^{-1} in the N-fertilized and mixed-legume pastures ($p = 0.752$).

3.4 | Sod suppression after interseeding effects

3.4.1 | 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 2020 (1755 vs. 2028 kg ha^{-1}, respectively; $p = 0.431$) or 2021 (2737 vs. 2956 kg ha^{-1}, respectively; $p = 0.487$). Applying glyphosate after interseeding pastures with sorghum × sudangrass significantly reduced perennial grass mass relative to the grazed, 0 kg ha^{-1} control in the summer sampling (Figure 3). 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 1), 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 increased legume mass later that summer by 116% relative

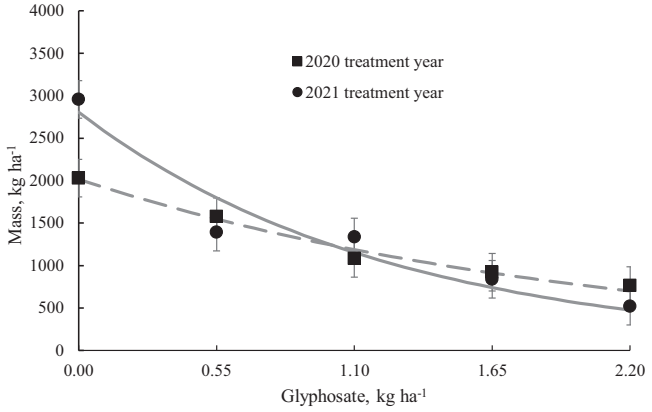


FIGURE 3 Perennial grass mass in summer as affected by glyphosate [N-(phosphonomethyl) glycine] rate after interseeding pastures with sorghum × sudangrass [*Sorghum bicolor* (L.) Moench × *S. bicolor* (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan] near Mead, NE. The summer sampling took place 8 weeks after treatment (i.e., August 5, 2020 and August 9, 2021). Heavy grazing by cattle (*Bos taurus* L.) in two rotational stocking cycles preceded the sorghum × sudangrass interseeding and glyphosate applications in spring each year. Each mean ± SE represents two pasture types and three replicates ($n = 6$).

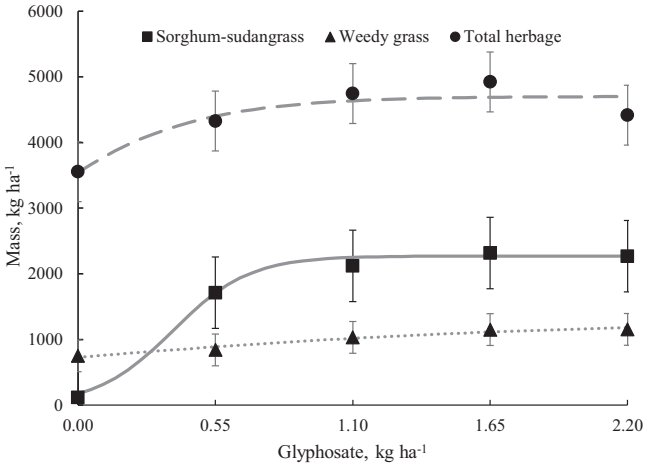


FIGURE 4 Sorghum × sudangrass [*Sorghum bicolor* (L.) Moench × *S. bicolor* (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan], weedy grass, and total herbage mass in summer as affected by glyphosate [N-(phosphonomethyl) glycine] rate after interseeding sorghum × sudangrass into pastures near Mead, NE. The summer sampling time took place 8 weeks after interseeding and sod suppression treatments (i.e., in August 2020 and 2021). Heavy grazing by cattle (*Bos taurus* L.) in two rotational stocking cycles preceded sorghum × sudangrass interseeding and the glyphosate treatment applications each year. Each mean ± SE represents two pasture types, 2 years, and three replicates ($n = 12$).

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 showed a logistic growth response to increasing glyphosate rate after interseeding (Figure 4; $y = 2269.4 / (1 + 12.1119e^{-6.5564x})$; $p < 0.001$). Indeed, sorghum × sudangrass mass increased from a low of 114 kg ha^{-1} in the grazed, 0 kg ha^{-1} control to a high of 2316 kg ha^{-1} in the 1.65 kg ha^{-1} glyphosate treatment. However, sorghum × sudangrass mass never differed beyond the 0.55 kg ha^{-1} glyphosate rate. Among the 0 kg ha^{-1} controlsy, 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 ($y = 1289.2 / (1 + 0.7687e^{-0.9559x})$ and total herbage mass $y = 4701.5 / (1 + 0.3271e^{-2.8482x})$ also had significant fits with logistic growth models as glyphosate rate increased (Figure 4; $p < 0.001$). Mowing and removing herbage that had been stockpiled 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 grazed, 0 kg ha^{-1} control when glyphosate rate 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; $p = 0.393$).

3.4.2 | 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 1). However, perennial grass mass again showed a significant fit with an exponential decay model in response to increasing glyphosate rate (Figure 5; $y = 4302.2e^{-0.3339x}$; $p < 0.001$). 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 1). 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

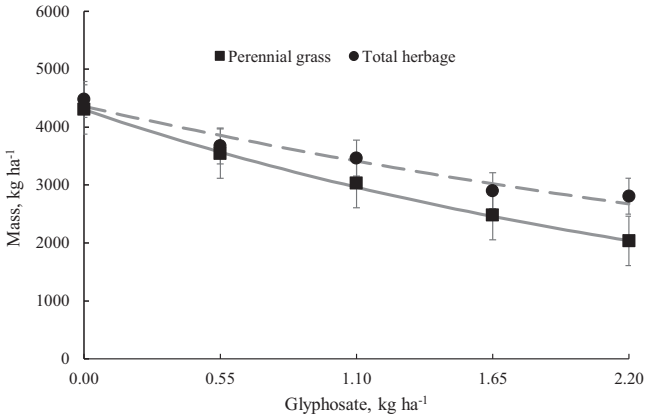


FIGURE 5 Perennial grass and total herbage mass in the next spring as affected by glyphosate [N-(phosphonomethyl) glycine] rate after interseeding sorghum × sudangrass [*Sorghum bicolor* (L.) Moench × *S. bicolor* (L.) Moench ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan] the previous spring in pastures near Mead, NE. The next spring sampling time took place 50 weeks after interseeding and sod suppression treatments (i.e., in May 2021 and 2022). Heavy grazing by cattle (*Bos taurus* L.) in two rotational stocking cycles preceded sorghum × sudangrass interseeding and the glyphosate treatment applications during the previous spring, but grazing was excluded before the May 2021 and 2022 samplings. Each mean ± SE represents two pasture types, 2 years, and three replicates ($n = 12$).

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 5) relative to the sampling in the previous summer (Figure 4). 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 5). Among 0 kg ha^{-1} controls, mowing and removing herbage that had been 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; $p = 0.045$). 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 1).

3.5 | 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 2). In the next spring samplings in May 2021 and 2022, the 2020 treatment year was found to have greater perennial grass mass than the 2021 treatment year (Table 2). 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 2). 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 2).

TABLE 2 Herbage mass components in pastures near Mead, NE, as affected by treatment year.

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 herbage	2020	3515	3854
	2021	4801	3115
		**	**

Note: The summer sampling took place 8 weeks after interseeding and sod suppression (i.e., in August 2020 and 2021), while the next spring sampling took place 50 weeks after interseeding and sod suppression (i.e., in May 2021 and 2022).
#p 0.05 ≤ 0.10; *$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$.

4 | DISCUSSION

This study attempted to expand current literature on methods to improve interseeding of annual warm-season 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 annual warm-season forage success as cool-season perennial grass production diminishes as temperatures increase through summer. The practice has had variable success depending on the year and moisture availability (Guretzky et al., 2020; Harmoney

& 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 in spring before interseeding on the treatment paddocks. Rotational stocking periods one and two were intended to deplete leaf area and root carbohydrate reserves of the existing perennial vegetation and thereby enhance success of the sorghum × sudangrass 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 the two stocking periods in spring before interseeding sorghum × sudangrass. In both interseeding years, 2020 and 2021, precipitation was below average at planting in June (Figure 2), 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 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, 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 but did not differ significantly beyond 0.55 kg ha^{-1} glyphosate applied.

A downside of herbicide use 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 with the glyphosate treatment.

Low precipitation in fall 2020 and spring 2021 may have affected the ability of smooth bromegrass 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 2020, cumulative precipitation was 118 mm, whereas the historical average was 198 mm (Figure 2). 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 late May 2022.

During the summer sampling, pasture type did not significantly affect perennial grass mass but in the next spring sampling, the N-fertilized pastures had greater perennial grass mass than the 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 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 it has been shown that application of glyphosate at 0.48 kg ha^{-1} on vegetative alfalfa significantly reduces its mass compared to nontreated alfalfa (Arregui et al., 2001). The glyphosate effect in our study may not have been detected 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 × sudangrass, indicating that heavily grazing alfalfa with short rest periods may negatively affect its productivity.

Spring does not seem to be a problematic time for weedy grasses and forbs. However, once summer reduces the growth of cool-season forage species such as smooth bromegrass, 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 about 400 kg ha^{-1} at glyphosate rates exceeding 1.10 kg ha^{-1}. Reducing

perennial grass competition with glyphosate likely benefitted the weeds and may have reduced growth of the interseeded sorghum × sudangrass. However, presence of some grassy weeds may be advantageous in grazing systems by increasing herbage mass and nutritive value, particularly during the summer slump of perennial cool-season grass pastures. 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 crabgrass had greater in vitro true digestibility (IVTD) across the entire summer than tall fescue, while yellow foxtail had greater IVTD until August 28. When more glyphosate was applied, herbage mass in the summer exceeded the control, and indeed, weedy grass and total herbage mass showed logistic growth responses to increasing glyphosate rates, indicating greater overall productivity of the system in the summer sampling. 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.

Although we did not have non-seeded controls in this study, previous research at this study site has not observed effects of interseeding sorghum × sudangrass on legume mass, but non-seeded areas have 22% greater perennial grass mass than interseeded areas (Guretzky et al., 2023). This would mean a non-seeded, 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 3; 2029 or 2956 × 1.22). Sorghum × sudangrass interseeding has also 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, that is, 990 kg ha^{-1} (Figure 3; 750 × 1.32) in the grazed control. In a non-seeded control where herbage was mowed and removed after stockpiling throughout spring, weedy grass mass in the summer sampling likely would have been 1%–56% greater, that is, 80–123 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).

5 | CONCLUSION

This experiment showed that glyphosate may be used for sod suppression to improve annual warm-season forage interseeding into existing perennial cool-season grass pastures. As glyphosate rate increased, sorghum × sudangrass and total herbage mass showed logistic rather than linear growth, reaching near maximum amounts with 0.55 kg ha^{-1} of glyphosate applied. However, our recommendation to practitioners interseeding pastures with annual warm-season forages is to mow and remove existing herbage after stockpiling it throughout spring before interseeding, as opposed to using glyphosate or grazing alone as forms of sod suppression. When using glyphosate coupled with grazing for sod suppression, practitioners should expect more herbage mass to be weedy grasses than when using mowing for sod suppression. Glyphosate use will reduce perennial grass mass the next spring, a penalty offsetting increased herbage gains in summer due to sorghum × sudangrass interseeding. When haying smooth bromegrass or utilizing glyphosate as a chemical suppressant, we recommend fertilizing pastures with 90 kg N ha^{-1} the next spring to improve perennial grass recovery. If pastures contain legumes, springtime N fertilization may be unnecessary due to symbiotic N_2 fixation and subsequent N cycling through rhizosphere exchange, cattle defecation, and urination.

AUTHOR CONTRIBUTIONS

Matthew Jenkins: Data curation; visualization; writing—original draft. **Heidi Hillhouse**: Conceptualization; data curation; investigation; methodology; project administration; supervision; validation. **John A. Guretzky**: Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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