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Fall grazing improves the performance of Kernza intermediate wheatgrass as a dual-purpose crop

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Abstract

Kernza intermediate wheatgrass (IWG) [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey] is a perennial grain and forage crop with novel dual-use potential. Grazing IWG forage and/or intercropping IWG with legumes can increase total annual forage yields, but the effect of grazing timing on grain yield needs to be understood to maximize producer returns and the productivity of the perennial stand. In this study, we compared Kernza grain and forage yields under different cattle grazing timing treatments (spring, fall, or spring and fall) with ungrazed IWG stands, in both IWG monocultures and IWG–legume intercrops. We established the experiment in the fall of 2016 at Morris, MN, and Lancaster, WI, and collected data over 3 years. In the first grain production year, grazing spring vegetative regrowth reduced Kernza grain yield compared with ungrazed stands in both Minnesota (213 vs. 360 kg ha^{-1}, respectively) and Wisconsin (821 vs. 1030 kg ha^{-1}, respectively). However, grazing fall regrowth after summer grain and straw harvest did not negatively affect grain yield in the following year compared to the ungrazed control. Intercropping IWG with legumes increased accumulated forage vegetative regrowth in Wisconsin, but not in Minnesota. Overall, our study confirms IWG's potential as a dual-purpose crop under grazing management and recommends fall grazing to minimize adverse effects on subsequent grain yields. Future research should focus on refining grazing strategies to maximize dual-use productivity.

Plain Language Summary

Kernza intermediate wheatgrass (IWG) is a new perennial grain and forage crop. Grazing IWG forage and/or intercropping IWG with legumes can increase total annual forage yields, but the effect of grazing timing on grain yield needs to be understood to maximize producer returns. In this study, we compared Kernza grain and

Abbreviations: ADF, acid detergent fiber; AU, animal units; CP, crude protein; IWG, intermediate wheatgrass; m a.s.l., meters above sea level; NDF, neutral detergent fiber.

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forage yields under different cattle grazing timing treatments (spring, fall, or spring and fall) with ungrazed IWG stands, in both IWG monocultures and IWG–legume intercrops. We established the experiment in two locations in US Midwest and collected data over 3 years. In the first grain production year, grazing spring vegetative regrowth reduced Kernza grain yield compared with ungrazed stands. However, grazing fall regrowth after summer grain and straw harvest did not reduce grain yield in the following year compared to the ungrazed control. Our study confirms IWG's potential as a dual-purpose crop under fall grazing management.

1 | INTRODUCTION

Integrating crop–livestock systems is a key form of ecological intensification needed for achieving future food security and environmental sustainability (De Faccio Carvalho et al., 2021; Lemaire et al., 2014). Including forages in rotation with grain crops increases perenniality and biodiversity, benefiting ecosystem services like habitat provisioning for wildlife, soil retention, and water quality protection (Franco et al., 2021). Moreover, integrating livestock can enhance nutrient cycling, fostering circular agricultural systems, and benefit farmer livelihoods by replacing off-farm input purchases and diversifying income sources (Garrett et al., 2017; Picasso et al., 2022; Ryschawy et al., 2017). Historically, crop/livestock integration has involved alternating field crops with pasture or forage, grazing livestock on crop residues, and/or grazing livestock on cover crops. However, recent advances in domestication and breeding of perennial cereals for seed yield offer a new opportunity for crop–livestock integration, since farmers can harvest seed and forage from the same plant stand.

Perennial grain crops are becoming a viable option for farmers due to emerging markets that include price premiums for crops grown using regenerative practices (Cureton et al., 2023). Particularly, intermediate wheatgrass (IWG) [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey] is among the most promising dual-purpose perennial crops to date (Lanker et al., 2020). IWG could largely nullify agricultural nitrate loading to ground and surface waters (Culman et al., 2013; Jungers et al., 2019), and unlike annual crops, serve as an atmospheric carbon sink rather than a source (De Oliveira et al., 2020; Wiesner et al., 2022), all while providing habitat for wildlife and contributing to biodiversity preservation (DeHaan & Ismail, 2017). Grain harvested from advanced breeding lines of IWG is sold as Kernza to restaurants, bakeries, and other food-related businesses in the United States for use in grain food products (Lubofsky, 2016; Ryan et al., 2018). After harvesting Kernza grain, the remaining vegetative material (which we refer to as "straw") can be harvested and mixed with higher value forage, such as alfalfa hay, to feed beef cows or dairy heifers (Pizarro et al., 2025, 2026), or can be used as bedding. In spring or fall, IWG wheatgrass vegetative regrowth is suitable for lactating beef cows, dairy cows, and growing heifers, as is typical of other cool-season grasses commonly grown in the humid climate of the Upper US Midwest (Culman et al., 2023; Favre et al., 2019).

The dual purpose of Kernza IWG, for both grain and forage, makes it a potentially profitable alternative for farmers (Law, Wayman, Pelzer, Culman, et al., 2022; Pinto et al., 2022). Kernza grain yields are typically one-fourth to one-third of annual grain counterparts (494–1075 kg ha^{-1}) and sharply decline in the fourth year (Culman et al., 2023; Zhen et al., 2024). While breeding progress is expected to increase grain yields in future variety releases, the current low grain yields motivate exploration of other biomass harvesting processes to supplement income from Kernza grain. Similar to annual small grains, harvesting straw along with grain during the summer harvest represents proverbial "low hanging fruit" as small grains farmers are already accustomed to the practice, and straw markets are readily available. Across nine diverse environments of North America, Kernza straw yields averaged 6.0 Mg ha^{-1} in the first year, 4.5 Mg ha^{-1} in the second year, and 5.7 Mg ha^{-1} in the third year (Culman et al., 2023). A drop in the harvest index was observed, from 12% to 4% in older stands, suggesting that the percentage of revenue that comes from forage has greater weight in the old stands (Law, Wayman, Pelzer, Culman, et al., 2022; Pinto et al., 2022).

Although IWG vegetative regrowth in spring and fall is usually low in terms of harvestable dry matter biomass, its high quality increases the nutritive and potential economic value of the forage. In a large study comprising nine sites across the US Midwest, spring forage production was 1.3–1.7 Mg ha^{-1} and fall forage production was 1.2 and 1.9 Mg ha^{-1} (Culman et al., 2023). Although adding a spring or fall harvest represents only around a 30% increase in the amount of annual forage harvested, it increases the average relative feed value from 74–82 to 83–95 (Culman et al., 2023). In addition to the benefits of having an extra forage harvest, previous studies have highlighted the possibility of beneficial impacts of forage harvest on grain yield (Culman et al., 2023; Hunter, Sheaffer, Culman, & Jungers, 2020; Pinto, De Haan, et al., 2021). Since

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reproductive tiller initiation can be reduced by shade in older cool-season grass stands (Chastain & Young, 1998), it has been hypothesized that fall defoliation increases the proportion of reproductive tillers the following year. However, lower harvest indices have been observed in IWG systems with a fall forage removal than without any forage removal. In contrast, spring forage removal has increased the harvest index but decreased overall grain yields in the same growing season (Culman et al., 2023; Hunter, Sheaffer, Culman, & Jungers, 2020).

Forage harvest could either be beneficial or detrimental to grain production, depending on frequency, timing, and form, whether by mechanical cutting or grazing. Cutting and removing the forage twice in the year, in the summer and in the fall (Culman et al., 2023) or three times in the spring, summer, and fall (Hunter, Sheaffer, Culman, & Jungers, 2020), has increased the grain yield compared to not removing any forage in the second year. To date, most dual-use studies on IWG have investigated the effects of mechanical forage removal, and the effect of grazing has not been evaluated. There are many reasons to expect that grazing and mechanical harvest could have differing effects on IWG grain and forage production. Grazing has potential benefits in terms of nutrient cycling because more than 70% of the nitrogen consumed by grazing livestock returns to the soil via manure and urine (Piñeiro et al., 2010), where organic forms of the nitrogen in the plant biomass are redeposited as urea in urine and dung patches. However grazing, if not managed with best management practices, could lead to a greater risk of soil compaction and erosion and physically damage perennial grass crowns and winter survival structures by rubbing, trampling, and browsing (Fleischner, 1994; Lunt et al., 2007).

Effects of grazing may differ between IWG monocultures and IWG intercropped with legumes. Growing legumes with perennial grasses can provide multiple benefits, including providing N inputs by biological fixation (Jensen et al., 2020; Pinto, Rubio, et al., 2021; Reilly et al., 2022), suppressing weeds (Law, Wayman, Pelzer, DiTommaso, et al., 2022), and increasing total forage and its nutritive value (Favre et al., 2019; Pinto et al., 2022). This latter benefit is particularly vital in grazing systems which, unlike feedlot systems, have limited scope for balancing livestock diets by adding feed concentrates (especially for protein). However, while legumes bolster productivity and nutritional balance, they also face the risk of being overgrazed. Such selective grazing can gradually reduce the legume proportion while leading to an increase in weeds over time (Eldridge et al., 2016). Implementing strategic grazing management, aimed at promoting a uniform selection across species by adjusting stocking density and grazing intensity, can mitigate this issue (Pittarello et al., 2019). Moreover, legumes in the Kernza stand could compete with Kernza for water and soil nutrients, leading to interspecific competition-mediated yield reductions in Kernza grain yields, despite their forage benefits. Nevertheless, predicting outcomes in such a novel system that includes Kernza IWG dual-purpose crops, legumes, and livestock remains a complex endeavor. This is why the research questions we want to address in this project are as follows: (1) How does the timing of grazing affect Kernza grain yields, summer forage yield, and total annual forage yield when livestock graze in spring, fall, or both spring and fall? (2) Do these effects differ when IWG is intercropped with legumes versus IWG monoculture?

Core Ideas

- Fall grazing does not reduce Kernza grain yields and provides an additional forage output.
- Spring grazing reduced Kernza grain yield in the first year and had variable impacts in subsequent years.
- Intercropping with legumes did not have effects on forage yield due to low legume proportions.
- Kernza intermediate wheatgrass (IWG) can be effectively harvested for grain and forage in the summer with additional grazing in the fall.

2 | MATERIALS AND METHODS

2.1 | Site description and IWG establishment

The experiment was established in the fall of 2016 at two locations: the University of Minnesota Morris West Central Research and Outreach Center (Minnesota, 45°38′ N, 95°54′ W, 345 m a.s.l. (where m a.s.l. is meters above sea level) on a Tara silt loam (fine-silty, mixed, superactive, frigid Aquic Pachic Hapludoll) and at University of Wisconsin-Madison Lancaster Agricultural Research Station (Wisconsin, 43°18′6.97″ N, 89°21′9.98″ W, 321 m a.s.l.) on a Fayette silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs). The mean annual temperature and rainfall are 5.7°C and 683 mm in Morris, MN, and 7.9°C and 836 mm in Lancaster, WI. Soil pH was 8.0, and concentrations of nitrate-N was 2 ppm in Morris, P was 2.2 ppm, and K was 131 ppm, in the first summer (June 2017), while in Lancaster soil pH was 6.7 with nitrate-N at 5.5 ppm, ammonium-N at 8.3 ppm, P at 18.8 ppm, K at 115 ppm, 2.56% organic matter, 1219 ppm Ca, and 410 ppm Mg in the first fall (September 2016).

Prior to IWG planting, the previous crop in Minnesota was soybean harvested for forage, and in Wisconsin, the previous crop was a 3-year-old alfalfa pasture (in two blocks) and an oat field (harvested in June, in the third block). Fields were treated with herbicide twice (a mix of glyphosate and

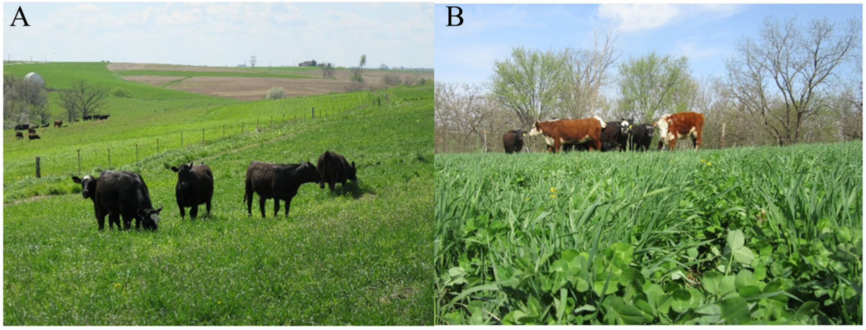

FIGURE 1 Pictures of intermediate wheatgrass Kernza grazing experiment in Lancaster, WI. (A) Kernza monoculture in spring 2017. (B) Kernza–red clover intercropping in spring 2018.

ammonium sulfate) at least 2 weeks before no-till planting. IWG was seeded using The Land Institute's selection Cycle 4 germplasm (Zhang et al., 2016) at a depth of 6–10 mm. In Minnesota, IWG was seeded on September 19, 2016, with a no-till drill at 38 cm row spacing at a rate of 25 kg seed ha^{-1}. Alfalfa (*Medicago sativa* L., 'Red Falcon') was seeded the following spring on May 11, 2017, with a Brillion seeder at 16.8 kg seed ha^{-1}. In Wisconsin, IWG was seeded on September 15, 2016, at 11.9 kg seed ha^{-1} in 38 cm row spacing with a Great Plains 1006NT no-till drill, with inoculated red clover (*Trifolium pratense* L., 'Forage First 9615′) seeded in inter-rows at 14.9 kg seed ha^{-1}. In Minnesota, fertilizer consisted of 71 kg N ha^{-1}, 8 kg P_2O_5 ha^{-1}, and 107 kg K_2O ha^{-1} applied as hog nursery manure on June 8, 2018, and 90 kg N ha^{-1}, 68 kg P_2O_5 ha^{-1}, and 45 kg K_2O ha^{-1} applied as chicken manure on June 13, 2019. In Wisconsin, fertilizer application included 68 kg N ha^{-1}, 34 kg P_2O_5 ha^{-1}, and 84 kg K_2O ha^{-1} broadcasted in spring 2017 (with P, K, and half of the rate of N on April 10, and the remaining half of N applied on May 12), and 56 kg N ha^{-1}, 45 kg P_2O_5 ha^{-1}, and 84 kg K_2O ha^{-1} broadcasted on March 27, 2018.

2.2 | Experimental design

The experiment was conducted using a randomized complete block design with a split-plot arrangement of treatments, with three replications at each location. The treatment design was factorial, with two factors: grazing and intercropping. Grazing treatments consisted of four different timings and frequencies: ungrazed (no grazing), spring (single grazing in spring), fall (single grazing in fall), and spring + fall (both grazing in the spring and in the fall). Grazing treatments were short-duration, high-intensity (i.e., mob stocking; Allen et al., 2011), with the goal of removing forage biomass but not damaging plant growth points (Figure 1). The spring grazing occurred when IWG plants were in a vegetative stage, about 30 cm tall, and the first node was identified in the stem about 2.5 cm from the plant crown (E1 stage; Moore et al., 1991). In Minnesota, the spring grazing was conducted on June 6, 2017, May 31, 2018, and June 1, 2019, using 30 Holstein heifers (90 AU ha^{-1} [where AU is animal units]), while in Wisconsin, it took place on May 4, 2017, May 7, 2018, and May 3, 2019, with 78 dairy heifers (96 AU ha^{-1}). Fall grazing was performed approximately 2 months after the Kernza grain harvest and prior to the first frost. In Minnesota, fall grazing occurred on November 13, 2017, with 31 Holstein–Hereford heifers (105 AU ha^{-1}) and November 26, 2018, with 25 Holstein–Hereford heifers (84 AU ha^{-1}), while in Wisconsin, it occurred on October 18, 2017, and October 16, 2018, with 28 beef steers (46 AU ha^{-1}).

The intercropping factor consisted of IWG monoculture and IWG intercropped with a legume (alfalfa in Minnesota and red clover in Wisconsin). Whole plots were assigned to grazing treatments and subplots to intercropping treatments. In Minnesota, the subplot size was 222 m^2, and in Wisconsin, it was 506 m^2. Grazing events involved 12 subplots, considering three subplots assigned to single (i.e., only in the spring or fall) grazing IWG monoculture, three to single grazing intercropping, three spring and fall grazing IWG monoculture, and three spring and fall grazing intercropping. Portable electric fences were used to subdivide the paddocks, ensuring consistent grazing management across all treatments.

2.3 | Data collection

Forage availability was determined approximately 5 days prior to both spring and fall grazing by clipping biomass from 0.25 m^2 quadrat randomly placed in each plot. The biomass was sorted into IWG forage, legume forage (only in the intercropping treatments), and weeds. Then, the biomass was dried at 60°C for at least 5 days before being weighed.

Kernza grain and summer forage (IWG straw and legume forage) yields were sampled at IWG physiological maturity from a 0.42 m^2 quadrat randomly placed in each plot, on August 4, 2017, August 9, 2018, and August 14, 2019, in Minnesota, and on July 31, 2017, August 2, 2018, and July 26, 2019, in Wisconsin. Spikes were dried for 3 days at 55°C and threshed with a mechanical seed thresher (Wintersteiger research thresher). Kernza grain and summer forage were weighed, and data were adjusted proportionally to the num-

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ber of rows within the sampled quadrat, to obtain yields in kilograms per hectare. For intercropping, the accumulated forage was calculated as the sum of IWG and legumes, while in monocultures it corresponds only to IWG forage. The remaining grain and straw were machine-harvested with a combine and removed.

2.4 | Forage nutritive value

Forage samples collected before spring and fall grazings were ground and analyzed to estimate forage nutritive values for each species (i.e., crude protein [CP], neutral detergent fiber [NDF], and acid detergent fiber [ADF]). For the intercropping treatments, IWG and legume samples were analyzed separately, and the values for the mixture were calculated as a weighted average based on their proportion in the sample. The selected samples were first ground with a Christy hammer mill (Christy-Turner Ltd.) to pass a 1-mm screen. In Minnesota, forage nutritive values were predicted using near-infrared spectroscopy and validated based on samples analyzed with wet chemistry methods (Goering & Van Soest, 1970). In Wisconsin, all forage nutritive samples were analyzed using wet chemistry procedures. Total N was determined according to the Dumas combustion method (Method 990.03-AOAC, 2000), and the analysis was conducted in a LECO FP-528 (LECO Corporation). CP was calculated as N × 6.25. NDF and ADF were analyzed sequentially in an Ankom 2000 Fiber Analyzer (Ankom Technology) according to the procedure of Goering and Van Soest (1970) and modified by Hintz et al. (1996) to include sodium sulfite during refluxing. For the IWG–legume intercrops, CP, NDF, and ADF concentration of the mixture forage was calculated as the weighted average of IWG and legumes based on their respective biomass proportion of the total forage accumulation.

2.5 | Statistical analysis

Since the effect of fall grazing cannot be tested in the first summer harvest, in 2017 fall grazing was analyzed as ungrazed, and spring + fall grazing was analyzed as spring grazing. This allowed us to use all the available data to evaluate all the treatments applied each year, ensuring consistency in treatment classification across years. First, to evaluate the effect of stand age on Kernza grain and IWG summer forage yields, only the treatments applied in the 3 years (ungrazed and spring) were considered. We performed an analysis of variance where fixed effects were location, grazing, intercropping, and interactions, and age as a repeated measurement. Second, for Kernza grain yield, IWG forage, accumulated forage, and weed biomass variables, we performed an analysis of variance per location and age where fixed effects were grazing, intercropping, and their interactions. For legume forage, we tested the grazing effect only. Third, to compare the availability of vegetative regrowth in each season, we performed an analysis of variance per location where fixed effects were age, season, intercropping, and their interactions for IWG and accumulated forage, age, season, and interactions for legume forage. In all the analyses, block and the interaction intercropping-by-block were used as random effects.

3 | RESULTS AND DISCUSSION

3.1 | Effect of grazing and intercropping on Kernza grain yield

Grazing and intercropping effects on Kernza grain yields differed among locations and years (Table S1). In the first grain production year, grazing spring vegetative regrowth reduced Kernza grain yields compared to ungrazed stands both in Minnesota (213 vs. 360 kg ha^{-1}, respectively) and Wisconsin (821 vs. 1030, kg ha^{-1}, respectively) sites (Table 1; Figure 2). In Minnesota, grain yields were much lower than typically observed in the region (Zhen et al., 2024), likely due to the experiment being conducted on a low-fertility field with a substantial seedbank of common ragweed (*Ambrosia artemisiifolia* L.). Spring grazing further promoted ragweed growth, potentially reducing competition from the establishing Kernza. In the second year in Minnesota, when grain yields were almost negligible, treatments that received grazing of vegetative regrowth once per year in either spring or fall produced a similar Kernza grain yield as ungrazed stands. However, grazing in both spring and fall reduced grain yield compared to ungrazed IWG (26 vs. 64 kg ha^{-1}, respectively). In the third year in Minnesota, when grain yields recovered (possibly because of fertilization), both spring-only grazing and spring plus fall grazing had lower grain yield than ungrazed IWG stands (150 vs. 334 kg ha^{-1}, respectively; Figure 2), and spring plus fall grazing had lower grain yield than fall-only grazing. In contrast, grazing had no effect on Kernza grain yields in Wisconsin during the second and third years (321 and 122 kg ha^{-1} on average, respectively; Figure 2).

Previous studies have shown that Kernza grain yields typically decline in the years following initial harvest (Culman et al., 2023; Zhen et al., 2024). However, in Minnesota, Kernza grain yields under ungrazed treatments in the third year were similar to the first year. As the lowest grain yields were observed in the second year, one possible explanation for the recovery of Kernza grain yields is the organic manure amendments applied in the spring of the second and third years. Furthermore, Kernza grain yields in the first year were lower compared with what was previously observed at the

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TABLE 1 Analysis of variance (*p*-values) for effects of grazing (ungrazed: no grazing, spring: single grazing in spring, fall: single grazing in fall, and spring + fall: both grazing in the spring and in the fall); intercropping (intermediate wheatgrass [IWG] Kernza monoculture and Kernza–legume intercropping); and their interactions (G × I) on IWG forage, legume forage, accumulated forage (IWG + legume), and weeds in Minnesota and Wisconsin in the first, second, and third grain production year.

Location	Age	Effect	Grain	IWG forage	Legume forage	Accumulated forage	Weeds
Minnesota	First	Grazing	<0.01	0.02	0.64	0.02	<0.01
		Intercropping	0.66	0.41		0.36	0.29
		G × I	0.25	0.88		0.86	0.4
	Second	Grazing	0.04	0.07	0.84	0.15	0.32
		Intercropping	0.15	0.51		0.37	0.18
		G × I	0.94	0.99		0.99	0.54
	Third	Grazing	<0.01	<0.01	0.93	0.03	0.05
		Intercropping	0.05	0.29		0.19	0.07
		G × I	0.03	0.24		0.57	0.86
Wisconsin	First	Grazing	0.03	0.93	0.89	0.84	0.55
		Intercropping	0.08	0.33		0.14	0.98
		G × I	0.23	0.38		0.44	0.46
	Second	Grazing	0.25	0.69	0.03	0.6	0.24
		Intercropping	0.99	0.17		0.55	0.51
		G × I	0.89	0.15		0.13	0.9
	Third	Grazing	0.12	0.52	0.50	0.52	0.84
		Intercropping	0.20	0.98		0.58	0.23
		G × I	0.41	0.05		0.13	0.28

same location (Tautges et al., 2018), and usually, no grain decline is observed when starting with a low initial grain yield (Fernandez et al., 2020; Pinto, De Haan, et al., 2021; Sakiroglu et al., 2020). In Wisconsin, Kernza grain yield was 928 kg ha^{-1} on average in the first year and there was a grain decline of 66% in the second year, and an extra 62% in the third year (Figure 2).

The lack of positive effects of grazing vegetative regrowth on Kernza grain yield aligns with previous research results from a study with vegetative regrowth mechanical harvest (Culman et al., 2023). In that study, they found that harvesting forage in summer or summer and fall led to higher Kernza grain than leaving the summer straw in the field (Culman et al., 2023). That positive response seems to be associated with a higher light availability that favors reproductive tiller initiation, which could instead be limited in old Kernza stands that are heavily shaded by accumulated forage (Chastain & Young, 1998). The lack of additional benefit from fall forage removal indicates that this does not trigger important changes in light availability in systems where summer straw is removed every year.

In Minnesota, the first-year spring-seeded alfalfa did not fully establish until Year 3. In this year, legume intercropping lowered Kernza grain yield compared to the monoculture but only under the ungrazed treatment (Table 1; Figure 2). In Wisconsin, Kernza grain yields in the first year decreased by intercropping with red clover (1070 kg ha^{-1} for the IWG monoculture and 781 kg ha^{-1} for IWG–legume intercropping; Figure 2). Although the overall grazing by intercropping interaction was not significant (Table 1), contrast analysis showed that under spring grazing, Kernza grain yields were higher in monoculture than in the intercropping (adj. $p = 0.03$).

3.2 | Effect of grazing and intercropping on summer forage yield

Grazing only affected summer IWG forage in the first and third years in Minnesota (Figure 3). In the first year, grazing spring vegetative regrowth resulted in lower summer IWG forage yield than ungrazed IWG stands (1490 vs. 2460 kg ha^{-1}, respectively). In the third year, grazing in the spring or both spring and fall had lower summer IWG forage yields compared to ungrazed treatment (2640 vs. 4650 kg ha^{-1}, respectively) but single fall grazing (3550 kg ha^{-1}) was not different from the ungrazed treatment. In Wisconsin, IWG summer forage was 6680, 6760, and 4520 kg ha^{-1} in the first, second, and third grain production years, respectively, and grazing did not affect summer forage in any year. Previous research, using forage cutting rather than grazing, has shown that spring forage cutting reduces summer IWG forage in the first, second, or third year (Culman et al., 2023). Although

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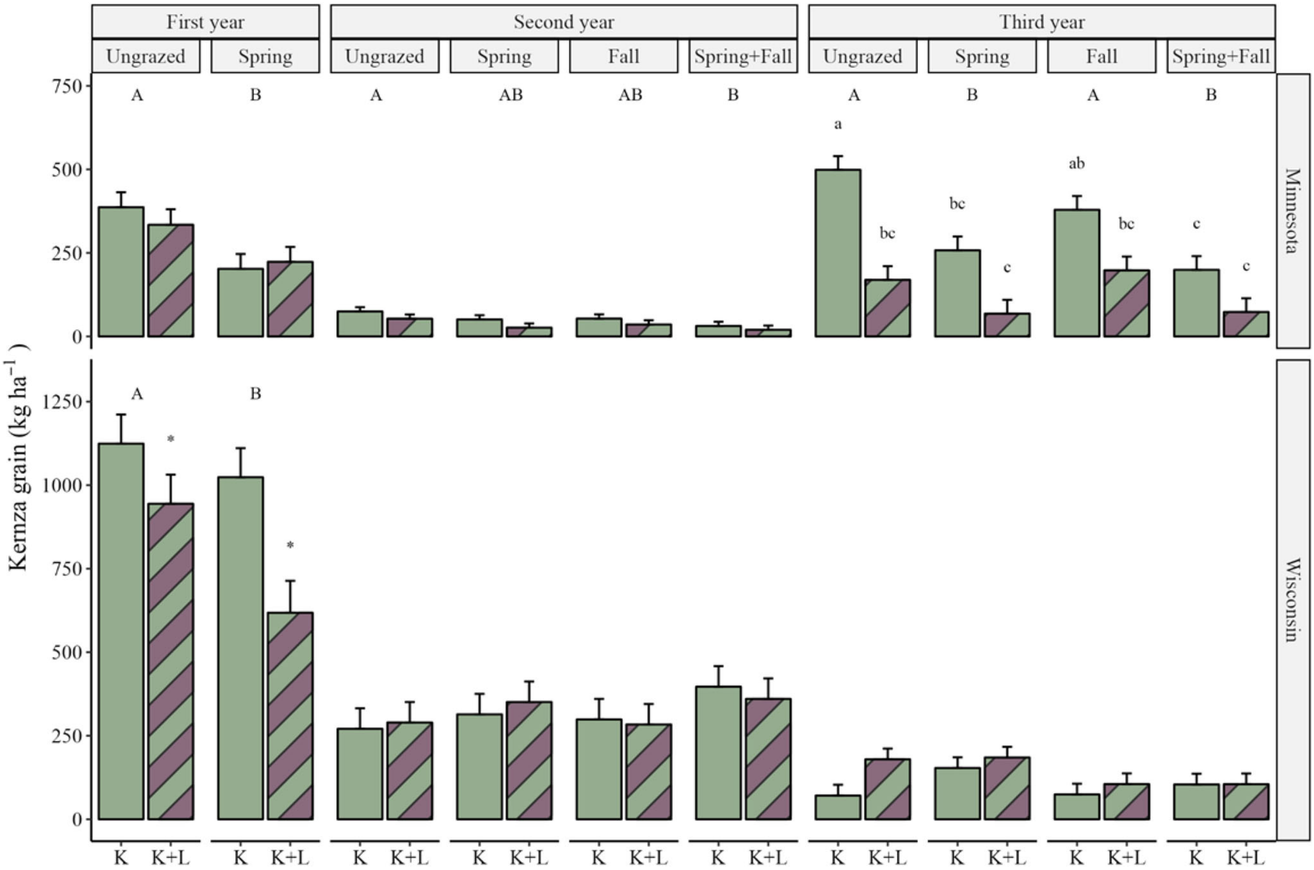

FIGURE 2 Kernza grain yields (mean and standard error [SE], kg ha^{-1}) for four grazing timing treatments (ungrazed: no grazing, spring: single grazing in spring, fall: single grazing in fall, and spring + fall: both grazing in the spring and in the fall) in Minnesota and Wisconsin. Plain columns represent intermediate wheatgrass (IWG) Kernza monoculture (K) and striped columns represent Kernza–legume intercropping (K + L). In the first grain production year, only "ungrazed" and "spring" treatments are depicted, as no fall treatments were applied by grain harvest (summer). Capital letters indicate differences among grazing treatments within location and years (p-values < 0.05; Table 1). Lowercase letters indicate differences in the grazing × intercropping (G × I) interaction within location and years (p-values < 0.05; Table 1).

spring or fall vegetative regrowth in Wisconsin was similar to that study, the lack of grazing effect may be attributed to the fact that grazing typically removes less forage than cutting, especially in studies with short grazing durations like ours (Sollenberger et al., 2005).

Intercropping did not affect IWG summer forage or accumulated forage in any year (Table 1), and legume forage yield varied by location and stand age. In Minnesota, the alfalfa summer forage was 55, 606, and 1720 kg ha^{-1} in the first, second, and third grain production years, respectively, and it was not affected by grazing any year (Table 1). In Wisconsin, the red clover summer forage was 2740, 268, and 683 kg ha^{-1} in the first, second, and third grain production years, respectively, and it was affected by grazing only in the second year. There, fall grazing had a higher legume summer forage than the ungrazed treatment (437 vs. 147 kg ha^{-1}, respectively). There was no grazing by intercropping interaction for total summer forage in any year or location (Table 1). Previous studies of Kernza–legume intercropping showed variable effects on the accumulated forage. For example, Kernza intercropped with red clover systems had higher accumulated forage than in Kernza monoculture in previous studies in Arlington (WI) and New York (Favre et al., 2019; Law, Wayman, Pelzer, DiTommaso, et al., 2022). However, neither red clover nor other legumes (i.e., alfalfa, alsike clover, white clover, Canada milkvetch, birdsfoot trefoil, berseem clover, and kura clover) increased the accumulated biomass compared to IWG monoculture (Pinto et al., 2022, 2024; Reilly et al., 2022).

Grazing and intercropping effects on grain and forage yields were minimally reflected in the harvest index. In Minnesota, the harvest index was 16%, 2%, and 6% in the first, second, and third year, respectively, but grazing did not affect the harvest index in any year (p = 0.22, p = 0.27, and p = 0.13 in the first, second, and third year, respectively). In the third year, alfalfa intercropping reduced the harvest index compared to IWG monoculture (4% vs. 8%, respectively, p = 0.03) but there was no grazing by intercropping interaction (p = 0.68). In Wisconsin, intercropping did not influence harvest index in any year (p = 0.34, p = 0.71,

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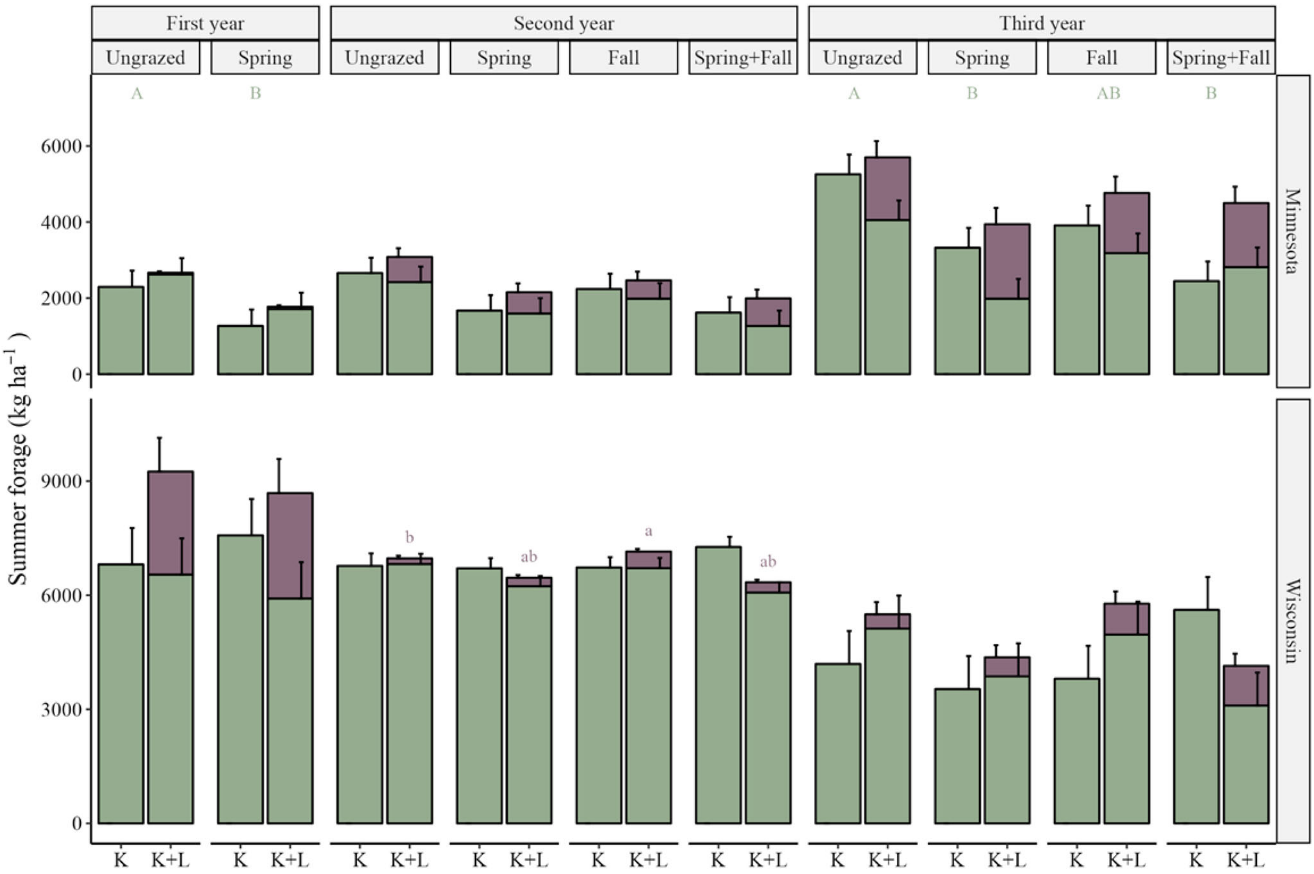

FIGURE 3 Summer intermediate wheatgrass (IWG; green) and legume (purple) forage (mean and standard error [SE], kg ha^{-1}) for four grazing timing treatments (ungrazed: no grazing, spring: single grazing in spring, fall: single grazing in fall, and spring + fall: both grazing in the spring and in the fall) in Minnesota and Wisconsin. In the first grain production year, only "ungrazed" and "spring" treatments are depicted, as no fall treatments were applied by grain harvest (summer). Single columns show IWG Kernza monoculture (K) and stacked columns show Kernza–legume intercropping (K + L). Capital green letters indicate significant differences among grazing treatments in the IWG summer forage (p-values < 0.05; Table 1). Lowercase purple letters indicate significant differences among grazing treatments in the legume summer forage (p-values < 0.05; Table 1).

and p = 0.15 in the first, second, and third year, respectively). Grazing only affected the harvest index in the third year (p < 0.01), when spring grazing had a higher harvest index than fall and spring plus fall grazing (5% vs. 2% on average). However, consistent with previous forage removal studies, these increases in the harvest index did not translate to higher overall grain yields (Culman et al., 2023; Hunter, Sheaffer, Culman, & Jungers, 2020).

3.3 | Summer weed biomass

Grazing only affected weed biomass in Minnesota in the first and third years (Table 1; Figure 4). In the first year, weed biomass in the summer after spring grazing was higher than the ungrazed treatment (2510 vs. 1160 kg ha^{-1}, respectively). High weed biomass in the first year may be one reason for the low initial Kernza grain yields at the Minnesota site. Particularly, under spring grazing there was more biomass accumulated by the weeds than by IWG (Figures 3 and 4). This suggests that grazing low biomass IWG stands is not recommended, since it can favor weed growth. In the third year, weed biomass was lower in the ungrazed treatment than in the combined spring and fall grazing treatment, but it did not differ from single grazing in Minnesota. In contrast, grazing did not affect weed biomass in Wisconsin (Figure 4). At this location, the negative effect of grazing on first-year grain yield (Figure 2) does not appear to be mediated by weeds. There was no grazing by intercropping interaction for summer weed biomass in any year or location (Figure 4).

3.4 | Availability of spring and fall forage vegetative regrowth by season

Our results suggest that grazing fall vegetative regrowth after summer grain and straw harvest can increase the total annual forage harvest in dual-purpose perennial crop systems. In Minnesota, the forage vegetative regrowth changed with the season and the year. Fall forage availability was three times

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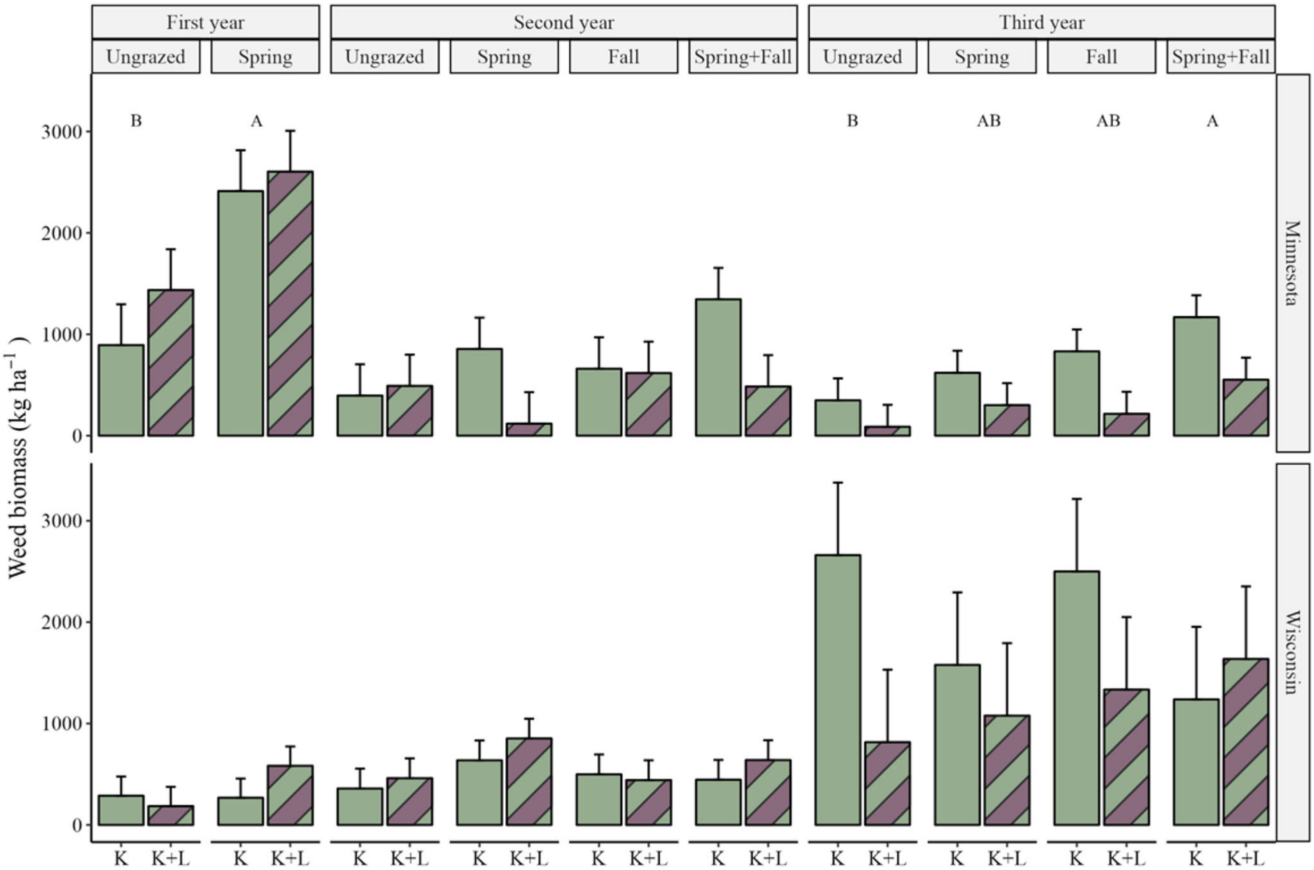

FIGURE 4 Summer weed biomass (mean and standard error [SE], kg ha^{-1}) for four grazing timing treatments (ungrazed: no grazing, spring: single grazing in spring, fall: single grazing in fall, and spring + fall: both grazing in the spring and in the fall) in Minnesota and Wisconsin. Plain columns represent intermediate wheatgrass (IWG) Kernza monoculture (K) and striped columns represent Kernza–legume intercropping (K + L). In the first grain production year, only "ungrazed" and "spring" treatments are depicted, as no fall treatments were applied by grain harvest (summer). Capital letters indicate significant differences among grazing treatments (p-values < 0.05; Table 1).

higher than spring availability in the first year, with no differences in the second year (Table 2). Those forage yields were lower than previously reported in Minnesota (1500 kg spring forage ha^{-1}, 2300 kg fall forage ha^{-1}; Hunter, Sheaffer, Culman, Lazarus, et al., 2020) even though the forage was sampled at similar or later dates. In contrast, season and year did not affect IWG forage yield in Wisconsin (1190 kg ha^{-1}; Table 2). This aligns with what was previously observed in a multi-site study across North America where fall and spring forage yields did not differ among years (Culman et al., 2023). In IWG monocultures, similar IWG forage yields in spring and fall could make it easier to decide when to graze if timing affects grain yields. However, in intercropping systems, both IWG and legume forage should be considered. The legume forage in the first year was negligible in Minnesota because alfalfa was frost-seeded that spring. In the second year, legume forage availability was 186 kg ha^{-1} and did not show differences between spring and fall seasons. In the third year, legume forage was higher than in the first year but similar to the second year (Table 2). In Wisconsin, red clover forage availability was higher in the fall of the first year than in the fall of the second year and in the spring of both years (Table 2). Overall, intercropping increased accumulated forage availability (IWG + legume) in Wisconsin (1720 and 1110 kg ha^{-1}, in intercropping and IWG monoculture, respectively) but not in Minnesota.

Although grazing did not significantly increase Kernza grain yield, it contributed additional outputs to the system through vegetative regrowth and the forage consumed by animals during mob grazing in both spring and fall (Table 3). In Minnesota, adding fall vegetative regrowth to the summer forage resulted in higher total annual forage than adding the spring vegetative regrowth in the first full year (from spring to fall) but there were no differences between other treatments (Table 3). In this location, the negative effect of spring grazing on the summer IWG forage was not compensated by the extra spring forage that single spring and combined spring and fall grazing treatments had. This agrees with a previous Minnesota study, where adding fall forage led to the greatest total annual forage and estimated net returns

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TABLE 2 Spring and fall vegetative regrowth (forage availability) for grazing in Minnesota and Wisconsin (mean and standard error [SE], kg ha^{-1}).

Location	Age	Season	IWG forage	Legume forage	Accumulated forage
Minnesota	First	Spring	344 (26)c		344 (26)b
		Fall	1416 (89)a	25 (10)b	1544 (89)a
	Second	Spring	460 (41)c	110 (29)ab	553 (41)b
		Fall	231 (28)c	98 (23)ab	317 (24)b
	Third	Spring	1044 (121)b	335 (68)a	1297 (97)a
Wisconsin	First	Spring	1224 (95)	299 (56)b	1445 (93)ab
		Fall	1026 (55)	955 (222)a	1982 (235)a
	Second	Spring	1278 (51)	363 (45)b	1694 (75)ab
		Fall	1214 (65)	103 (19)b	1226 (49)b

Note: Accumulated forage is the sum of intermediate wheatgrass (IWG) and legume. Different letters denote statistically different values for seasons and years within each location ($p < 0.05$).

TABLE 3 Effect of grazing (G), intercropping (I), and G × I interaction on total annual forage yields and means (standard error [SE]) for four grazing timing treatments (ungrazed: only summer forage, spring: spring vegetative regrowth + summer forage, fall: summer forage + fall vegetative regrowth, and spring + fall: spring vegetative regrowth + summer forage + fall vegetative regrowth) in Minnesota and Wisconsin in the first and second years. Different letters denote statistically different values for grazing treatments within locations ($p < 0.05$)

		First year	Second year
Minnesota		Total annual forage yield (kg ha^{-1})	
	Ungrazed	2751 (662)ab	2870 (483)
	Spring	1718 (38)b	2472 (313)
	Fall	3830 (363)a	2702 (225)
	Spring + fall	3255(465)ab	2436 (247)
		p-values	
	Grazing	$p = 0.02$	$p = 0.80$
	Intercropping	$p = 0.43$	$p = 0.31$
	G × I	$p = 0.30$	$p = 0.97$
Wisconsin		Total annual forage yield (kg ha^{-1})	
	Ungrazed	7994 (871)b	6721 (153)c
	Spring	9260 (960)ab	8057 (162)b
	Fall	9791 (1350)ab	8215 (251)b
	Spring + fall	12,013 (913)a	9847 (142)a
		p-values	
	Grazing	$p = 0.03$	$p < 0.01$
	Intercropping	$p = 0.06$	$p = 0.06$
	G × I	$p = 0.52$	$p = 0.52$

(Hunter, Sheaffer, Culman, Lazarus, et al., 2020). In Wisconsin, adding both spring and fall vegetative regrowth to the summer forage increased total annual forage but a single extra forage regrowth in spring or fall did not show differences to the ungrazed treatment (Table 3). Unlike previous forage harvest/cutting studies, total annual forage yields are overestimated in our study; while their harvest treatments remove all forage at 10 cm above the soil surface, our grazing treatments have left ungrazed between 20% and 40% of the available forage.

3.5 | Forage nutritive value

Forage nutritive values were influenced by both species and seasons. In Minnesota, alfalfa forage consistently had higher % CP and lower % NDF and % ADF than IWG across all

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TABLE 4 Mean (and standard error) of forage nutritive values (crude protein [% CP], neutral detergent fiber [% NDF], and acid detergent fiber [% ADF]) for harvested forage by location, species, and season.

Location	Species	Season	% CP	% NDF	% ADF
Minnesota	IWG	Spring	10.6 (1.2)c	67.7 (4.5)ab	37.2 (3.4)b
		Summer	5.4 (1.2)d	66.1 (4.5)b	38.1 (3.5)b
		Fall	8.2 (1.4)cd	74.8 (4.8)a	44.9 (3.6)a
	Alfalfa	Spring	18.9 (1.5)a	50.7 (4.8)c	35.3 (3.6)b
		Summer	16.7 (1.5)ab	45.8 (4.9)c	34 (3.6)b
		Fall	22.9 (1.9)a	47.1 (5.3)c	36 (3.9)b
	IWG + alfalfa	Spring	10.7 (1.6)c	63.2 (5)b	37.2 (3.7)b
		Summer	8.7 (1.5)cd	60.5 (4.9)b	37.1 (3.6)b
		Fall	12.3 (1.9)bc	70.5 (5.3)ab	45.2 (3.9)a
Wisconsin	IWG	Spring	21.6 (0.6)b	45.3 (2.6)de	24.9 (1.8)de
		Summer	4.4 (0.6)f	64 (2.5)a	40.9 (1.8)a
		Fall	14.4 (0.6)d	54.7 (2.5)b	30.8 (1.8)c
	Red clover	Spring	26.3 (1)a	30.9 (2.7)g	19.8 (1.9)f
		Summer	11.6 (0.7)e	50.6 (2.6)c	35.7 (1.9)b
		Fall	17.9 (0.7)c	40.2 (2.6)f	24.2 (1.9)e
	IWG + red clover	Spring	22.6 (1)b	41.7 (2.7)ef	23.9 (1.9)e
		Summer	7.1 (1)f	62.8 (2.7)a	42 (1.9)a
		Fall	16.2 (1)cd	47.6 (2.7)cd	27.1 (1.9)d

Note: Different letters denote statistically significant differences in species and seasons within each location ($p < 0.05$). Intercropping values were calculated as the weighted average of intermediate wheatgrass (IWG) and legumes based on their respective biomass proportions in the accumulated forage.

seasons (Table 4). However, the forage nutritive values of the IWG + alfalfa intercropping were not different from the IWG monoculture in any season due to the low legume proportion in the accumulated forage (Table 2). In Wisconsin, red clover had a higher % CP in the spring compared to the fall and summer (Table 4). Although IWG had consistently a lower % CP than red clover in each season, IWG spring regrowth had a higher % CP than red clover in the summer and fall (Table 4). Red clover also had lower % ADF and % NDF than IWG consistently in all seasons, with both species showing lower values in the vegetative regrowth in spring and fall compared to the summer (Table 4). Intercropping IWG + red clover had lower % NDF and % ADF than IWG monoculture in the fall, but there were no differences in the spring or summer nor in the % of CP in any season. The differences in the fall can be explained by the high legume proportion in the accumulated forage in Wisconsin (Table 2).

Species and seasonal trends in forage nutritive values are well established, and our values align with those previously reported in the literature (Coleman et al., 2010; Culman et al., 2023; Favre et al., 2019; Karn et al., 2006). Intercropping of IWG with red clover or alfalfa had mixed effects on forage nutritive values, largely influenced by the proportion of legume biomass in the accumulated forage. Particularly during the early growing season, low legume proportion may not provide substantial changes in forage nutritive value quality when compared to monocultures. While a higher proportion of legumes could improve forage quality (Pinto et al., 2022), their competition with IWG for resources might lead to a reduction in IWG grain yield (Pinto et al., 2024). This suggests that farmers should carefully manage the proportion of legumes in their intercropping systems, balancing the impacts on both forage quality and grain production to optimize overall revenue (Law, Wayman, Pelzer, DiTommaso, et al., 2022; Pinto et al., 2022).

4 | CONCLUSIONS

Our research tested grazing effects on dual grain–forage perennial cropping systems for the first time. Overall, our results support the potential of IWG as a dual-purpose perennial crop particularly when grazing fall regrowth after summer grain and straw. Similarities of grazing effect with the trends previously reported in studies where forage is cut and removed (Culman et al., 2023; Hunter, Sheaffer, Culman, Lazarus, et al., 2020) are promising. At least with the high intensity and short duration of mob grazing that we tested here, the potential unwanted effects of grazing such as compaction or damage to the vegetation (Fleischner, 1994; Lunt et al., 2007) were not observed. Both grazing and forage harvesting could increase the sustainability of farms, particularly those with limited resources, by increasing land use efficiency through multiple avenues of potential income generation. However, in terms

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of nutrient cycling, grazing requires less nutrient replacement than forage harvesting (Piñeiro et al., 2010), providing benefits in the long term.

Our findings further emphasize the importance of timing when integrating grazing into IWG systems. While spring grazing of vegetative regrowth consistently reduced summer grain yields in the first year, grazing fall regrowth after grain harvest did not negatively impact subsequent grain yields. Intercropping IWG with legumes increased accumulated forage availability in Wisconsin, but not in Minnesota. The relatively low proportion of legumes in the intercropping systems explains the lack of significant positive effects on forage nutritive values, as well as the absence of negative impacts on grain yields. Locations differed considerably in terms of responses due to weather and soil fertility, highlighting the potential range of system responses across diverse conditions. Overall, our results provide valuable insights for farmers considering IWG as a dual-use crop, offering a balanced approach to both forage and grain production.

AUTHOR CONTRIBUTIONS

Priscila Pinto: Data curation; formal analysis; investigation; methodology; software; visualization; writing—original draft; writing—review and editing. **Nicole E. Tautges**: Formal analysis; writing—review and editing. **Jacob M. Jungers**: Investigation; project administration; resources; supervision; writing—review and editing. **Craig C. Sheaffer**: Conceptualization; funding acquisition; methodology; project administration; resources; writing—review and editing. **Mitchell Hunter**: Data curation; formal analysis; writing—review and editing. **Valentin D. Picasso**: Conceptualization; funding acquisition; investigation; project administration; resources; supervision; visualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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