

PROCEEDINGS OF THE 2026
**GREAT PLAINS
SOIL FERTILITY
CONFERENCE**

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PROCEEDINGS OF THE 2026

GREAT PLAINS SOIL FERTILITY CONFERENCE

ORAL PROCEEDINGS



ASSESSMENT OF MICROALGAE AMENDMENTS ON SOIL NUTRIENT DYNAMICS AND COTTON PRODUCTIVITY UNDER LIMITED IRRIGATION IN TEXAS HIGH PLAINS

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ABSTRACT

Texas High Plains (THP) is a major cotton producing region of Texas. However, declining soil fertility and increasing risk of crop yield penalties associated with extreme weather patterns and low organic input have raised concern in sustainability of farmlands in this region. Micro-algae amendment is relatively new and emerging farm practice in crop production which is getting attention due to its ability to stimulate soil health and enhance crop productivity. There are no prior records on microalgae influence on soil nutrient availability and cotton productivity, especially in THP. The main objective of this study is to evaluate the impact of native microalgae amendment in soil nutrient availability and cotton productivity under deficit irrigation in THP. A field study was conducted during cotton growing season of 2025 at Texas A&M AgriLife Research Halfway center in a randomized complete block design with two irrigation levels: high and low rate and three algae treatments no algae-control (A1), high rate of algae (A2), and low rate of algae (A3) which were randomized with four replications. Results indicate that microalgae ameliorated water stress in cotton by retaining more water in soil and enhanced growth and physiology under water limitation. We speculate that, with microalgae amendment, soil will be enriched with essential nutrients contributing to soil fertility and overall soil health.

SEEDING RATE AND PLANTING CONFIGURATION AFFECT THE INTERSPECIFIC FUNCTION OF A WHEAT-PEA COVER CROP

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ABSTRACT

The ability of grass-legume cover crop mixtures to provide an appreciable N credit in semi-arid cropping systems is often limited by excessive competition and dominance of the grass. Inclusion of grass in the mixture is cost efficient and beneficial to the physical functions of cover crop residue and can facilitate greater legume N contribution by immobilizing available N, however there is a critical need to balance this function with the risk of over-competition. Field experiments were coordinated in the winter of 2024-2025 at Wall and San Angelo, TX to evaluate the effects of wheat seeding rate and alternative planting configurations on ultimate grass vs. legume biomass and N content in a wheat-Austrian winter pea cover crop mixture. Treatments comprised a 2 × 4 factorial with two planting configurations: species segregated (alternating) by drill row vs. combined (bulk) planted, and four wheat seeding rates: 150, 300, 450, and 600 thousand seed ac⁻¹ all planted with a constant rate of Austrian winter peas (110,000 seed ac⁻¹). Segregating species by drill row did not affect wheat biomass, but did increase pea biomass and N contribution each by ~65%. Pea biomass also increased with decreasing wheat seeding rate, and a wheat seeding rate of 300,000 seed ac⁻¹ optimized biomass accumulation of both species. These findings demonstrate potential to refine relative seeding rates and planting arrangements within cover crop mixtures, specifically within the semi-arid context of the Great Plains. A limitation of this work was that the wheat variety selected ('SY Razor') is extremely early-maturing, which increased spring competition with the legume, accelerated the timeline for termination, and ultimately restricted the peas potential for maximum biomass accumulation. This has informed ongoing work on varying maturities of winter cereals in cover crop mixtures, and should be considered with future efforts in this research area.

COVER CROP FUNCTION AND MANAGEMENT OPTIMIZATION FOR SEMIARID WEST TEXAS CROPPING SYSTEMS

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ABSTRACT

In semi-arid West Texas, cover cropping requires careful management to achieve a balance between water consumption and the desired agronomic benefits. A field experiment was conducted to evaluate the effects of four cover crop treatments: wheat, winter pea, a wheat-pea mixture, and a no-cover control under three termination timings and with or without supplemental nitrogen (N) fertilizer application. Biomass accumulation increased with delay in cover crop termination. Wheat grown alone produced the highest biomass, which did not differ from the wheat + pea mixture. Application of side-dress N fertilizer reduced late-season cover crop residue in all termination timings, and reduced cotton biomass only with early termination. Patterns of soil water storage corresponded with cover crop biomass production. Across all termination timings, fallow stored more soil water than cover-cropped plots. Total water storage under cover crops was 6-20% lower than fallow at early and intermediate timings, and 7-10% lower at the late termination. Cover crops terminated at early and intermediate timings did not influence yield whereas late termination reduced lint yield by ~11%. Lint yields did not differ among termination timings with fallow and pea treatments, but did vary with wheat and the wheat + pea mixture where delayed termination resulted in a 17-18% yield reduction. Preliminary findings of this work support that optimal termination timing depends on the cover crop species and its functional role. This knowledge can help refine cover crop management strategies to reduce risk while maintaining beneficial functions and may facilitate the strategic design of cover crop options and mixtures.

INTRODUCTION

The integration of cover crops into Texas cropping systems faces several challenges, which are often addressed individually rather than within a whole-system context. Bell et al. (2023) demonstrated substantial variability across Texas and concluded that optimized management practices are likely to vary as widely as the production environments themselves. Water use by cover crops is frequently cited as a major concern restricting adoption in dry regions. Nevertheless, comprehensive evaluations have shown that adequate cover crop residue, when combined with timely termination, is more likely to enhance soil water dynamics for the following crop (Burke et al., 2021). When yield reductions following cover crops cannot be attributed to water limitations, they are commonly linked to nutrient immobilization (Lewis et al., 2018; Bordovsky et al. 1998). These observations highlight the importance of clearly defining

the functional objectives of cover crops. In semi-arid West Texas, maintaining wheat stubble under fallow may provide a more economical and equally effective approach for reducing wind erosion and supporting soil water storage. However, if the goal is to utilize cover crops for nutrient contributions, particularly to reduce fertilizer inputs, then both the intended function and the associated management strategies must differ. The potential for legume nitrogen (N) contribution is supported (MacMillan et al., 2022), yet consistent benefits of cover crops to N cycling are not widely reported. These inconsistencies are largely attributed to differences in cover crop species and environmental conditions. To date, most studies evaluating cover crop mixtures in West Texas have used seeding rates dominated by winter cereals, typically rye. The inclusion of a grass species with a legume is hypothesized to create synergy between grass N scavenging and legume N fixation. However, winter cereals, particularly rye, are highly competitive, and mixtures frequently become grass-dominated, limiting the opportunity for the N-fixing species to contribute meaningfully. Earlier termination of cereal grains can reduce excessive nutrient immobilization and lower water use, but terminating too early reduces the benefit of in-season residue persistence. Conversely, later termination of legumes may increase N contribution but also increases cover crop water use. Aimed at identifying best management scenarios for our environment, the objectives of this study were therefore to i) quantify the effects of cover crop species composition and termination timing on biomass accumulation, nutrient cycling, and water dynamics, and ii) evaluate how these management strategies influence subsequent cotton growth and yield.

MATERIALS AND METHODS

A field experiment was conducted at Wall, Texas, using a randomized complete block design with four replications to assess cover crop treatments and management strategies. Main plots consisted of four cover crop treatments (wheat, Austrian winter pea, wheat + winter pea mixture, and no cover). Three termination timings, based on wheat growth stages (vegetative, boot, and anthesis), were assigned as split-plot treatments. Early-season fertilizer N side-dress application of 30 lb N ac⁻¹ versus no N fertilizer was included as a split-split-plot factor. Aboveground cover crop biomass was collected at each termination timing. Cotton biomass and the remaining aboveground cover crop residue were sampled at peak cotton growth (late bloom). Soil samples were collected to a depth of 24 inches at each termination timing and at late-season cotton and residue biomass sampling for gravimetric soil water content and nutrient analyses. Data were analyzed using mixed models, and treatment means were separated using Fisher's LSD ($\alpha = 0.05$).

RESULTS

Cover Crop Biomass

Wheat and the wheat-pea mixture produced greater biomass compared to pea alone (Figure 1A). Termination timing affected cover crop biomass accumulation, with later termination resulting in increased biomass accumulation (Figure 1B).

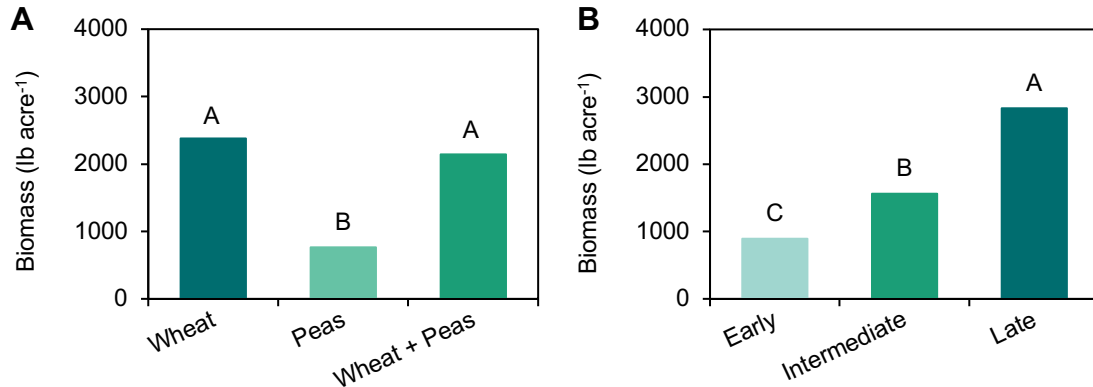


Figure 1. Measured cover crop biomass (A), and the effect of termination timing on cover crop biomass productivity (B).

Soil Water Dynamics

Soil water contents observed at 0-6", 6-12", 12-18", and 18-24" depths significantly varied among fallow and cover crop treatments within termination timings except for 0-6", 6-12", and 12-18" soil depths at late termination (Figure 2). Overall, fallow retained more soil water compared to cover crops whereas peas as a sole cover also resulted in similar soil water contents in some treatments and depths. These differences in soil water at cover crop termination corresponded with the relative biomass accumulation among treatments (Figure 1). Soil water content increased in 0-6", 6-12", and 12-18" soil depths in late termination which were not related to cover crop termination but were influenced by the rainfall events at later termination (Figure 2D). Total water storage under cover crops was 6-20% lower than fallow in early and intermediate terminations, and 7-10% lower in late termination, reflecting slightly higher soil moisture due to rainfall events (Figure 2D) during the late termination timing.

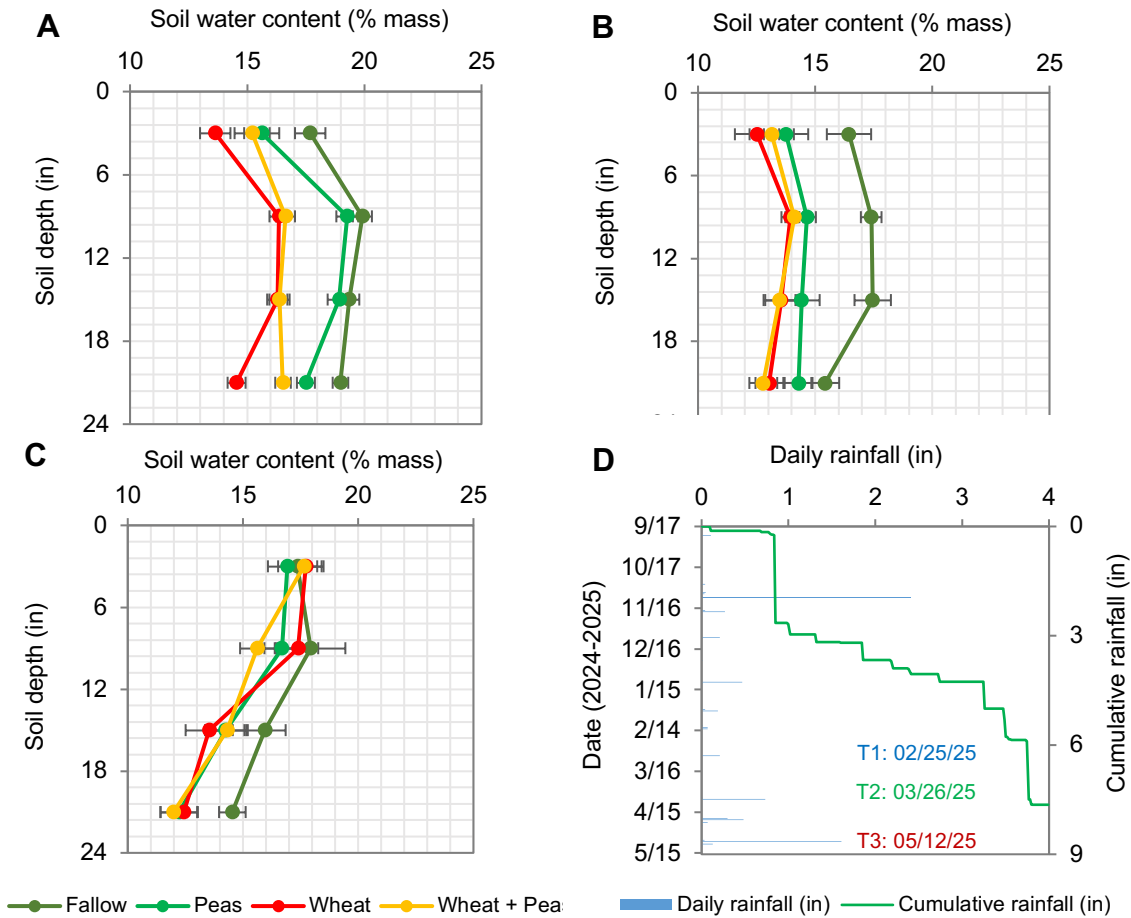


Figure 2. Soil moisture content at different soil depths for wheat, peas, wheat + peas, and fallow treatments at early (A), intermediate (B), and late (C) termination timings and daily and cumulative rainfall (in) from cover crop plantation to early (T1), intermediate (T2) and late (T3) terminations (D).

Cover Crop Residue and Cotton Biomass

Late-season cover crop residue was influenced by the interaction among wheat and wheat + pea cover crops, termination timing and fertilizer N applications. Side-dressed N decreased the amount of late-season residue for early and intermediate terminations of wheat + pea cover crops (Figure 3A), and reduced cotton biomass accumulation following early termination (Figure 3B). Ongoing analyses will determine whether this reflects a shift between vegetative and reproductive growth in fertilized versus unfertilized treatments.

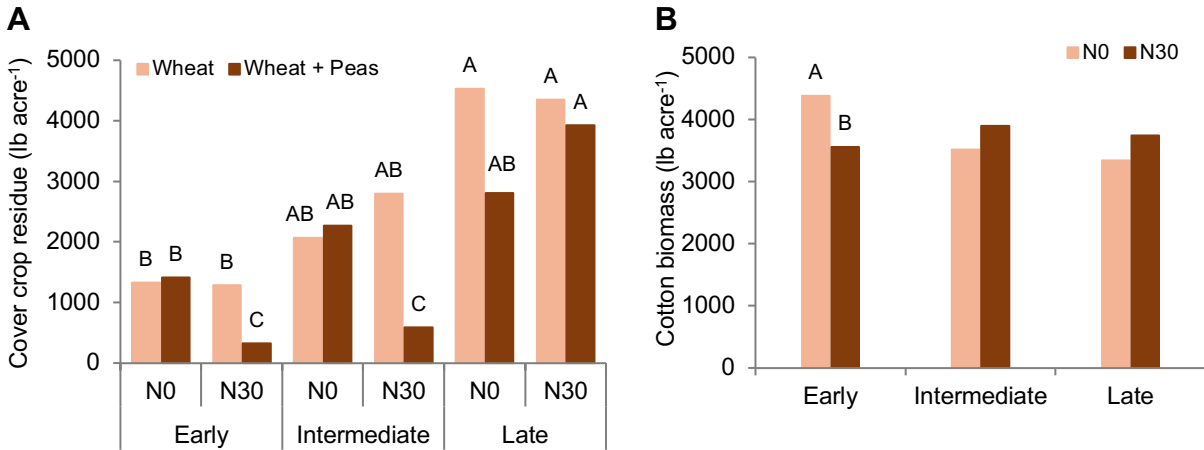


Figure 3. Interactive effects among termination timings and side-dressed N fertilizer applications for late season cover crop residue from wheat and wheat + peas cover crop mixtures (A) and effects of nitrogen fertilization on late season cotton biomass under different termination timings (B).

Cotton Lint Yield

Cotton lint yield was affected by the termination timing and the interaction between cover crops and termination timings (Figure 4). Lint yields were similar with early and intermediate cover crop termination, but yield was reduced by ~11% following later terminations (Figure 4B). Considering the interaction among cover crop management and termination timings, cotton lint yields did not differ among termination timings for fallow and pea treatments (Figure 4A). Among wheat treatments, delayed termination (intermediate and late) resulted in an 18% yield reduction compared to early termination. Similarly, the latest termination of wheat + pea treatment resulted in 17% lower cotton lint yields than the early termination, indicating that delayed termination can negatively affect cotton performance. These results highlight the importance of selecting appropriate cover crop species and optimizing termination timing to maximize or sustain subsequent cotton yield.

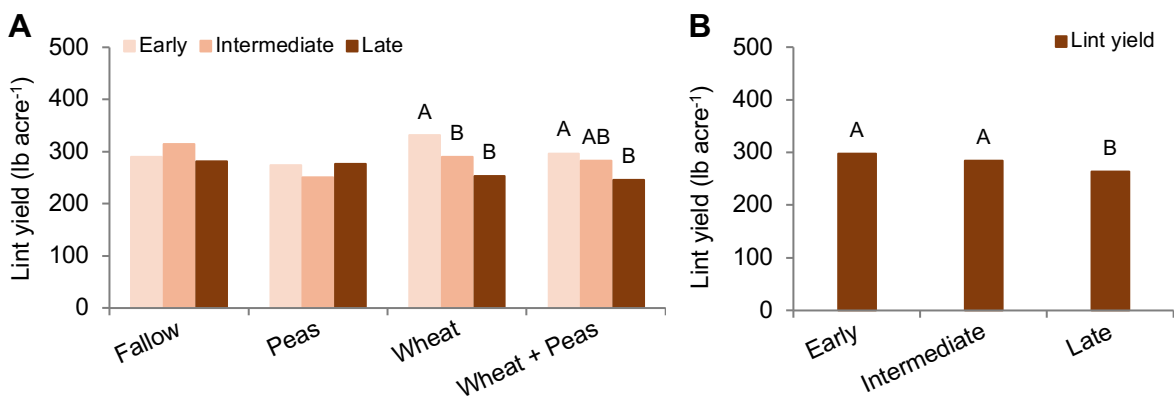


Figure 4. Cotton lint yields influenced by the interaction of fallow and cover crop treatments (wheat, peas, and wheat + peas) and different termination timings (A) and under the main effect of termination timings (B).

Summary

Findings from the first year of this project emphasize differences in biomass, growth timing, and maturity among cover crop species. These differences corresponded to predictable effects on soil water and subsequent cotton growth and yield, highlighting the direct risk of nutrient immobilization or soil water depletion with later termination of cereals, while showing no disadvantage with timely termination of wheat or delayed termination of the legume. The wheat variety used in this study was very early maturing, suggesting that a later-maturing variety could have produced different outcomes, particularly in a legume mix aimed at maximizing legume growth time while minimizing excessive nutrient immobilization by the cereal. The practical implications of these results indicate that terminating a wheat cover crop at boot did not negatively impact cotton production, whereas later termination did. In contrast, the earliest termination when wheat was at vegetative stage did not produce sufficient residue to persist through the cotton growing season. Nutrient analyses of cotton, cover crop, and soil samples from this study are ongoing, and the experiment is being repeated in 2026 to further inform cover crop management strategies in West Central Texas.

Acknowledgements

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COVER CROP PLANTING TIME EFFECTS ON BIOMASS PRODUCTIVITY, SOIL HEALTH AND WHEAT YIELD IN DRYLAND SYSTEMS

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ABSTRACT

Ecosystem benefits of cover crops (CCs) in semi-arid dryland cropping systems are dependent on CC biomass productivity. This study evaluated how CC planting time (spring vs. fall) and fallow management practices [no-tillage (NT) vs. occasional tillage (OT)] influenced CC biomass, surface residue, selected soil health properties and crop yields within a winter wheat (*Triticum aestivum* L.)-sorghum (*Sorghum bicolor* Moench)-fallow (WSF) rotation. The experiment was conducted from 2023 to 2025 at the Kansas State University Hearting Beason (HB) Ranch using a split-plot randomized complete block design with four replications. Main plots were cropping phases of the WSF rotation, while sub-plots included fallow management treatments: a fall-planted CC mixture of triticale, pea, and rapeseed; a spring-planted mixture of oat, pea and triticale; NT fallow and OT fallow. Fall-planted cover crops produced slightly more biomass than spring-planting though the difference was not statistically significant, indicating flexibility in planting time. Cover crops retained significantly more residue cover and increased soil organic carbon (SOC) in the top 0-2-in depth compared to fallow treatments. Soil bulk density was lower under fall-planted CCs and OT compared to NT fallow. Soils under CCs had greater water stable aggregates compared to NT or OT fallow indicating improved soil structure and overall soil health. Winter wheat yields were decreased by CCs but utilizing CC biomass as forage resource increased system profitability compared to fallow. Our findings showed either NT with CCs planted in the fall or spring can maintain soil health by increasing residue cover and soil aggregation in semi-arid dryland cropping systems.

INTRODUCTION

In semi-arid environments like the central Great Plains, improving soil health is crucial for water storage and sustainable crop production. Integrating CCs can play a significant role in enhancing soil properties, improving nutrient cycling, and increasing water retention. However, their effectiveness is highly dependent on CC biomass productivity. The timing of CC establishment influences growth duration, biomass accumulation, and soil health benefits, making it a critical factor for farmers and land managers in these water-limited environments. Cover crops contribute to soil health improvements by increasing organic matter, enhancing microbial activity, and reducing soil erosion. Early-planted CCs generally produce greater biomass due to an extended growing period, leading to improved soil cover and associated soil health benefits. Conversely, delayed planting may limit biomass accumulation due to shorter growth periods and reduced soil moisture availability, which are major concerns in semi-arid regions where precipitation is scarce.

In water-limited environments, improper timing of CCs can lead to soil moisture depletion, potentially competing with cash crops for water resources. However, when effectively managed, CCs can enhance soil infiltration, increase water retention, and promote wet aggregate stability, which contributes to improved soil resilience over time. This study investigated the effect of CC planting time (spring or fall) on CC biomass production, fallow management and CC effects on soil properties, wheat yield and profitability in a semi-arid cropping system. Understanding the relationship between CC timing, management strategies, and soil properties is essential for developing best management practices to improve soil sustainability and productivity in semi-arid environments.

Materials and Methods

This study is a component of a large CC field experiment initiated in spring 2015 at the Kansas State University experiment fields at HB Ranch near Brownell, KS. The overall goal of the CC trials was to develop climate-specific CC management options for integrating CCs into dryland crop production in western. The current study was established in fall 2023 to investigate the effects of CC planting timing and fallow management on biomass productivity, crop yields and soil physical properties. The study design was a split-plot randomized complete block with four replications. Crop phase was the main plot and split-plots treatments were oat (*Avena sativa* L.)–triticale (\times *Triticosecale* Wittm.) CCs grown during the fallow phase of the WSF rotation, planted either in the spring or in fall. Cover crops were managed as standing cover and were compared with NT and OT fallow treatments. The OT treatment was accomplished by tilling once in July or August during the fallow phase of the rotation prior to winter wheat planting to a depth of 3 inches using a sweep plow equipped with 5 feet blades and treaders (Premier Tillage Inc., Quinter, KS, USA). This is a non-inversion, a conservation tillage implement commonly used in the semi-arid CGP.

The CC biomass was determined by hand-clipping close to the ground level (~ 1 inch above the soil surface), two areas of 2 \times 3 ft per plot. Samples were dried at 122°F in a forced-air oven and weighed to determine dry matter. Oven-dried samples were ground to pass through a 1-mm mesh screen in a Wiley Mill (Thomas Scientific, Swedesboro, NJ). The ground samples were then analyzed for forage nutritive value [crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), *in vitro* dry matter digestibility (IVDMD)], tissue potassium (K) and phosphorus (P) concentrations (Ward Laboratories, Inc., Kearney, NE) using Foss 6500 near infrared spectroscopy (NIRS).

Intact soil samples were carefully obtained using a flat shovel to determine water stable aggregate stability. These samples were air-dried and gently passed through a 0.75-inch sieve to separate larger aggregates. Subsamples of <0.31-inch diameter aggregates were then obtained and used to estimate mean weight diameter (MWD) of water-stable aggregates (WSA) using the wet-sieving method. Residue cover was determined using the line transect method. Statistical analyses were completed in the SAS version 9.4 (SAS Institute, 2012, Cary, NC) using PROC GLIMMIX with year and treatment considered fixed and replication considered random. Treatment differences were considered significant at $P < 0.1$.

RESULTS AND DISCUSSION

Crop Yields and Net Returns

Averaged across years, fall-planted CCs produced more biomass (6080 lbs/ac) than spring-planted (4930 lbs/ac), but the difference was not statistically significant (Table 1). Spring-planted CCs had more CP, P, K and IVDMD concentrations compared to fall-planted CCs. However, ADF and NDF concentrations were not different between CC planting times. The CP requirement for growing replacement heifers with body weight (BW) of 1200 lb at maturity ranged from 8.1% (with growing BW of 960 lb) to 10.2% (with growing BW of 660 lb) assuming the forage contains $\geq 60\%$ total digestible nutrients (NRC, 2000). The average CP concentration of the fall or spring-planted CCs in this study were within the minimum CP requirement for growth or maintenance of grazing beef cattle. These results suggests that both planting times are viable options for maximizing CC biomass production and nutritive value (if used as forage), offering flexibility when CCs can be planted after sorghum in the WSF rotation.

Winter wheat yields were low in 2024 due to below average precipitation with an average of 25 bu/ac and no significant differences in yields across treatments. In 2025, there was no significant yield difference between NT and OT treatments. However, growing a fall-planted or spring-planted CCs decreased wheat yields but 20 bu/ac and 14 bu/ac, respectively (Figure 1). Net returns across years were least with fall-planted CCs, followed by spring-planted CC, while NT and OT had similar net returns. However, utilizing the CC biomass as forage increased net returns two-fold compared to the NT or OT fallow treatments (Figure 2). This agrees with previous studies that showed replacing fallow with CCs can decrease subsequent wheat yields in low-and high yielding years but haying CCs as forage increased profitability of the production system (Holman et al., 2021).

Residue Cover and Soil Properties

Residue cover measured at winter wheat planting were similar under fall-planted and spring-planted CCs, which were significantly greater than NT and OT treatments (Table 2). Although significantly lower than CCs treatments, the NT (70%) maintained adequate residue cover compared to OT (53%). The lower residue cover in OT is likely due to soil disturbance from tillage, which could accelerate residue decomposition. The higher residue cover with CCs and NT will armored the soil against erosion and potentially increase SOC accretion. The CC treatments increased SOC concentration and MWD of water stable aggregates in the 0-2-in depth (Table 2) but no differences were found among treatments in the 2-6-in depth. Similarly, growing CCs and OT decreased bulk density near the soil surface compared to NT. The distribution of water stable aggregates varied across treatments. The soils under fall and spring-planted CCs had the highest percentage of larger water stable aggregates, suggesting better soil stability (Table 3). These findings support other studies in western Kansas that showed growing CCs in place of fallow improved soil properties (Simon et al., 2021). In contrast, OT resulted in the smallest proportion of large aggregates and the highest amount of microaggregates. This finding indicates OT could break down soil structure and could predispose dryland soils to erosion. No-tillage treatment had a higher percentage of small macroaggregates (42%), showing that NT can preserve soil aggregation. Overall,

the results highlight that CCs regardless of planting time and NT help maintain healthier soil structure, while OT weakens soil aggregate stability.

Conclusion

This study highlights the impact of cover crop planting time on biomass production and soil properties in a semi-arid cropping system. Fall planting produced slightly more biomass than spring planting, but the difference was not statistically significant, suggesting flexibility in planting times for biomass production. Planting CCs in the fall resulted in more residue cover but soil improvement as indicated by aggregate stability and SOC was not different from spring-planted CCs. The OT had the lowest residue cover and aggregate stability due to soil disturbance from tillage. Growing CCs decreased wheat yields and net returns but utilizing CC biomass as forage increase profitability compared to fallow. Overall, cover cropping, either planting in the spring or fall and NT practices maintain soil health by increasing residue cover, improve SOC and soil aggregation in a dryland WSF cropping system.

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Table 1. Cover crop planting time effects on biomass produced and nutritive content averaged over 3 years at the Kansas State University experiment fields at HB Ranch near Brownell, KS.

Treatment	Biomass	CP†	ADF	NDF	IVDMD	K	P
Fall-planted	6083a‡	10.3a	32.1a	52a	66.5a	0.21b	1.56b
Spring Planted	4929a	12.1a	35.6a	57a	75.1a	0.27a	2.3a
p-value	0.207	0.007	0.27	0.3	0.14	0.001	0.001

†CP = crude protein. ADF = acid detergent fiber (higher values reflect lower digestibility). NDF = neutral detergent fiber (higher values reflect lower animal intake). IVDMD = *in vitro* dry matter digestibility (reflects relative energy differences).

‡Means within a column followed by the same letter (s) are not significantly different ($P < 0.05$).

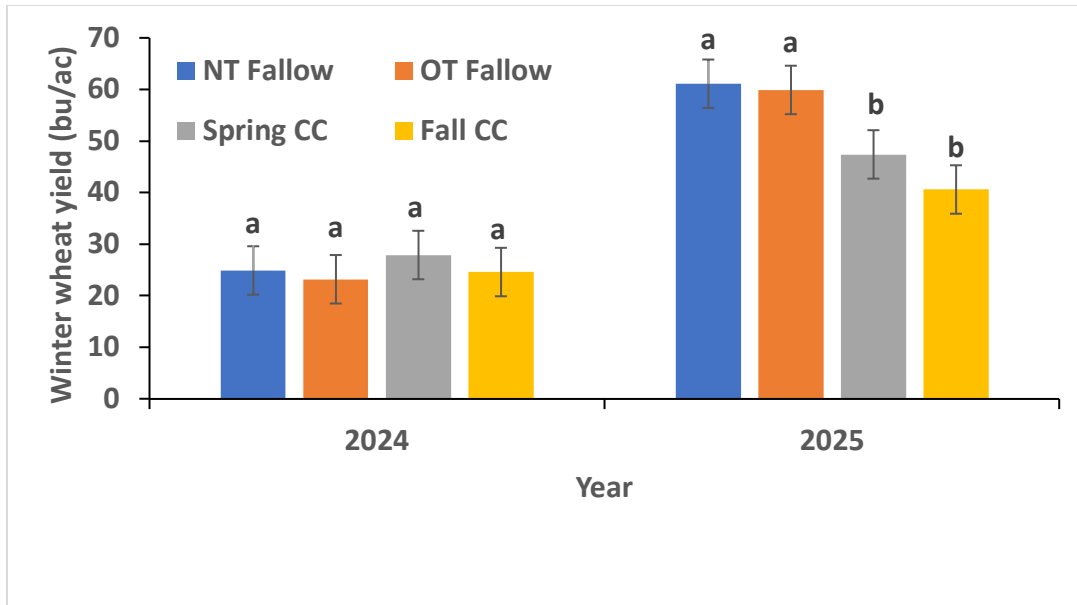


Figure 1. Cover crop planting time and fallow management effect on winter wheat yields at HB Ranch near Brownell, KS. Means followed by the same letter (s) are not significantly different ($P < 0.1$).

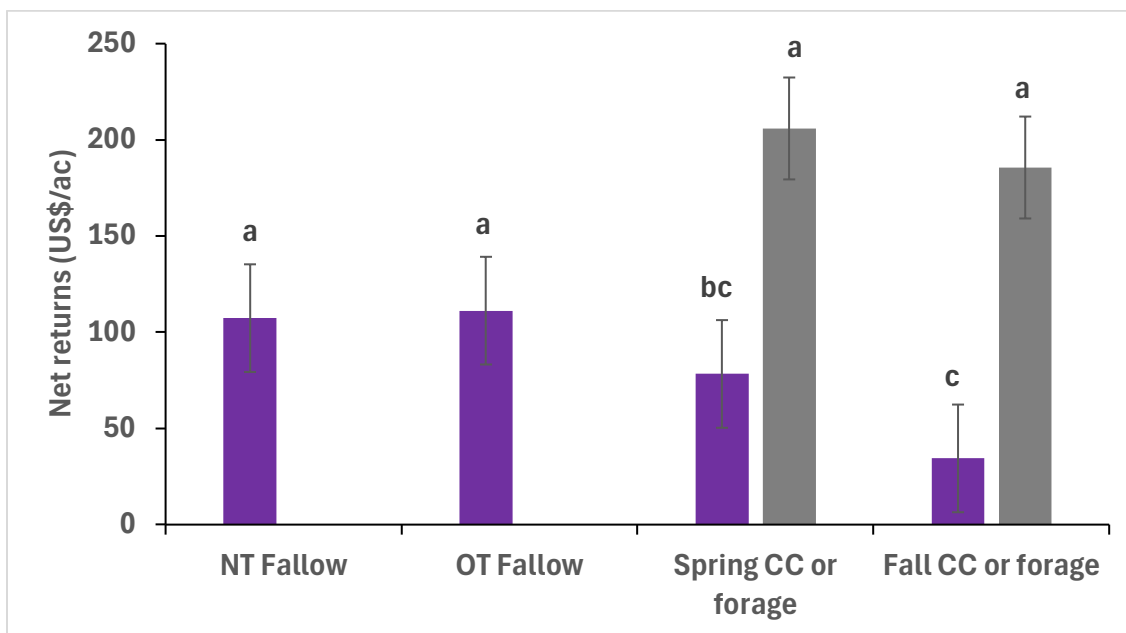


Figure 2. Profitability of wheat-sorghum-fallow rotation as affected by cover crop or forage crop planting time and fallow management. Means followed by the same letter (s) are not significantly different ($P < 0.1$).

Table 2. Cover crop planting time and fallow management effects on residue cover, bulk density, soil organic carbon (SOC) and mean weight diameter (MWD) of water stable aggregates measured in 0-2-in depth in 2023 and 2024 at the Kansas State University experiment fields at HB Ranch near Brownell, KS.

Treatment	Residue cover	Bulk density	SOC	MWD
	%	g/cm ³	%	mm
Fall Planted	84a	1.20a	1.50a	0.92ba
Spring Planted	83a	1.26ab	1.47ab	0.98a
NT Fallow	70b	1.33a	1.41b	0.65c
OT fallow	53c	1.19b	1.39b	0.73bc

Means followed by the same letter within a column are not significantly different ($P < 0.10$).

Table 3. Cover crop planting time and tillage affected water stable aggregate size distribution measured in the 0-2-in depth in 2023 and 2024 at the Kansas State University experiment fields at HB Ranch near Brownell, KS.

TRT	>2mm (%)	2-0.25(%)	<0.25mm (%)
Fall Planted	11.9a	35.9ba	52.3b
Spring Planted	12.1a	38.9ba	48.9b
Occasional Tillage	6.8b	31.3b	61.8a
No Tillage	7.4b	41.9a	50.6b

Means followed by the same letter within a column are not significantly different ($P < 0.10$).

CROP PRODUCTION AND SOIL PROPERTIES IMPACTS OF INTEGRATING ANNUAL FORAGES AND LIVESTOCK IN WHEAT-BASED CROPPING SYSTEMS

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ABSTRACT

Integrating annual forages and livestock can increase profitability but potentially negatively impact soil health in dryland cropping systems due to residue removal. The objective of this study was to determine crop yield and soil property impacts of integrating annual forages and livestock in traditional winter wheat (*Triticum aestivum* L.)-grain sorghum (*Sorghum bicolor* Moench)-fallow rotation (W-GS-F). Initiated in 2021 near Hays Kansas, treatments included W-GS-F (control), W-GS-F with GS residues grazed (W-GSG-F), wheat/forage sorghum-forage sorghum-fallow (W/FS-FS-F) with FS grazed (W/FSG-FSG-F), and FS hayed (W/FSH-FSH-F) in a randomized complete block design with four replications. Full-season FS harvested for hay averaged 6,546 lb/ac, while post-wheat FS averaged 2,582 lb/ac. Each harvesting period left ~30 % of biomass remaining as residue. Before grazing, full-season FS produced 6,184 lb/ac with ~50 % of biomass remaining as residue after livestock removal. Post-wheat FS plots were grazed in 3 out of 5-years, and produced 2,632 lb/ac before grazing with ~60 % of biomass remaining as residue post-graze. Wheat and grain sorghum yields did not differ across treatments. Soil cover and properties were sampled prior to wheat planting each sampling year. The W/FSG-FSG-F had the most soil cover and least penetration resistance. No differences in bulk density were observed when averaged across the 0-6 in depth. Despite no differences in bulk soil organic carbon (SOC), dry aggregate associated SOC was greater with W-GSG-F and W/FSG-FSG-F than W-GS-F and W/FSH-FSH-F in nearly all aggregate sizes. Soil nitrogen (N) and phosphorus (P) concentrations were not significantly different among treatments. No differences in mean weight diameter (MWD) of water stable aggregates were observed among treatments. Dry-aggregate MWD was similar for W-GS-F, W-GSG-F, and W/FSG-FSG-F treatments, but was significantly less for W/FSH-FSH-F. Percent wind erodible fraction (WEF) was consistently higher for W/FSH-FSH-F. Cropping system net returns varied by year and were significantly greater for W-GSG-F and W/FSG-FSG-F followed by the W-GS-F and least in the W/FSH-FSH-F due to far greater expenses. Overall, integrating annual forages and livestock improved or maintained soil health compared to the control, and was more profitable than haying forages.

INTRODUCTION

Intensifying dryland cropping systems with annual forages and integrating ruminant livestock have the potential to increase profitability, enhance fallow water use efficiency, and improve soil health by increasing residue cover and reducing wind and water erodibility. Currently, the most common crop rotation in this region is winter wheat (W) (*Triticum aestivum* L.)-summer crop-F. The most common summer crops utilized

within that rotation are grain sorghum (GS) (*Sorghum bicolor* (L.) Moench) and corn (*Zea mays* L.) (Schlegel et al., 2002). Typically, after the summer crop is harvested, a 12-14-month fallow period ensues to build soil water content for the next wheat crop. Due to high evaporation in this climate, only 17-30% of precipitation is retained as stored soil moisture during the fallow period (Peterson & Westfall et al., 2004). Even with no-till (NT), less than 40% of precipitation is retained, and soil cover is lost. Intensifying the rotation with annual forages may reduce soil water and have a negative impact on subsequent grain yield, but the forage that is produced for grazing and haying may offset negative impacts to profitability. Adding annual forages in wheat-based systems may even boost profitability (Holman et al., 2018, 2021, 2023a, 2023b; Carr et al., 2020). Concerns also may arise with the potentially negative impacts of haying and grazing on soil organic carbon (SOC) reserves, water stable aggregates, and wind erodible fraction due to removal of crop residue. Grazing is often perceived negatively because it may increase soil compaction as indicated by greater bulk density (BD) and penetration resistance (PR). The objective of this study was to analyze crop yield and soil health impacts of intensifying the traditional NT W-GS-F system with annual forages, as well as integrating livestock to graze forages and crop residues.

Materials and Methods

This study was initiated at the Kansas State University Agricultural Research Center-Hays near Hays, KS with all phases of the experiment in place by 2021. The study design was a randomized complete block with four replications in a W-GS-F rotation system. The study compared the W-GS-F rotation with grazing of the GS stalks and with grazing or haying of annual forage sorghum grown in place of GS. Each crop phase and hayed or grazed treatments were present each year. Plots were 90-ft wide x 127-ft long for the grazed treatments, and 30-ft wide x 127-ft long for the hayed treatments. Each treatment was grown under NT conditions.

Treatments:

1. Year 1: winter wheat; Year 2: grain sorghum; Year 3: fallow: (W-GS-F)
2. Year 1: winter wheat; Year 2: grain sorghum (grazed stalks); Year 3: fallow: (W-GSG-F)
3. Year 1: winter wheat/double-crop forage sorghum (grazed); Year 2: forage sorghum (grazed); Year 3: fallow: (W/FSG-FSG-F)
4. Year 1: winter wheat/double-crop forage sorghum (hayed); Year 2: forage sorghum (hayed); Year 3: fallow: (W/FSH-FSH-F)

Winter wheat was planted the end of September, GS and FS were planted at the beginning of June, and post-wheat FS was planted as soon as wheat was harvested. Winter wheat was harvested mid-late June, and GS was harvested mid-October. All grain crops were harvested using a Massey Ferguson 8XP plot combine with a 5-ft header. Grain yields were determined by a single 5-ft x 127-ft pass with the combine. Hayed FS was harvested at the end of August, at a 6-in cutting height. Forage sorghum yields were determined by a single harvest of a 3-ft x 127-ft pass with a Carter forage harvester at heading. Grazing of GS stocks occurred post GS harvest and at heading in FS. To determine FS amount before grazing and haying, a 2-ft x 3-ft quadrant was used

to sample two different locations within the plot. After grazing, the sampling was repeated to determine amount of residue remaining.

In August 2023-2025 after the full rotation cycle, soil samples were taken from each plot pre-wheat planting. The soil properties examined were residue cover (RC), wet and dry aggregate stability, BD, PR, SOC, N and P. Residue cover was quantified using the line transect method at two random locations within a plot. Two intact soil samples were collected per plot for aggregate stability and BD, while ten samples per plot were collected for all other soil property analyses. Wet aggregate stability mean weight diameter (MWD) was conducted by the wet sieving method using intact soil samples collected at the 0-2-in depth (Nimmo and Perkins, 2002). Dry aggregate stability was determined using a set of rotary sieves and wind erodible fraction was estimated as proportion of aggregates <0.84 at the 0-2-in depth (Chepil, 1962). Wet and dry aggregates were then analyzed for SOC for the >2mm, 2-0.25mm, and <0.25mm size distributions using the dry combustion method (Helmke et al., 2013). The same method was repeated for bulk SOC at 0-2-in and 2-6-in depths. The POM in samples was determined using the procedure outlined by Cambardella and Elliot (1992) at 0-2-in and 2-6-in depths. Bulk density was determined by the core method with samples taken from 0-2-in and 2-6-in depths (Grossman and Reinsch, 2002). Penetration resistance was determined using an Eijkelkamp Hand Penetrometer (Eijkelkamp Soil & Water, Morrisville, NC). A partial budget approach was used to estimate cropping systems net returns. Net returns were calculated using revenue accrued from each rotation system minus associated production costs after each treatment completed a full cycle. Statistical analyses were completed in the SAS version 9.4 (SAS Institute, 2012, Cary, NC) using PROC GLIMMIX with year and treatment considered fixed and replication considered random. Treatment differences were considered significant at $P \leq 0.1$.

RESULTS AND DISCUSSION

Crop Yields

Available forage mass varied yearly regardless of planting time. Full-season FS production was highest in 2025 (7,421 lb/ac) and lowest in 2022 (5,114 lb/ac). Post-wheat FS produced a maximum of 4,520 lb/ac in 2024, and a minimum of 741 lb/ac in 2022 due to limited soil moisture. Forage mass remaining as residue was significantly impacted by harvest type in both full-season and post-wheat FS production. Overall, grazing full-season FS left approximately 3,091 lb/ac of biomass on the soil surface, which represented 50% of the total above ground biomass. Haying of full-season FS left 1,963 lb/ac as residue, about 30% of total forage mass produced.

Post-wheat forage mass remaining was analyzed in 2021, 2024, and 2025. Treatments were not grazed or hayed in 2022 and 2023 because of limited production. Similar to the full-season forage mass, the grazed treatment had significantly more residue remaining on the soil surface (1516 lb/ac) than the hayed treatment (982 lb/ac).

Winter wheat yields were analyzed in 2023-2025, after each treatment completed a full cycle. Yields were low due to below average precipitation in every year but 2025, with an average of 23 bu/ac and no significant differences in yields across treatments. Grain sorghum yields were recorded in 2024 and 2025 after treatments had completed a full cycle. Again, there was no significant yield difference between the grain sorghum

treatments (W-GS-F and W-GSG-F), with an average grain yield of 67 bu/ac, limited by precipitation.

Residue Cover

In August 2023, W/FSG-FSG-F had the greatest RC (78%) (Fig. 1). The next highest treatments were W-GS-F (61%) and W/FSH-FSH-F (56%). With W-GSG-F (41%) leaving the least soil cover. However, RC was not significantly different among treatments in 2024, but W/FSG-FSG-F trended higher while W/FSH-FSH-F ranked last. In 2025, residue cover in W/FSG-FSG-F (85%), W-GSG-F (78%), W-GS-F (76%) were not significantly different from one another, but had significantly more RC than the W/FSH-FSH-F (59%) treatment.

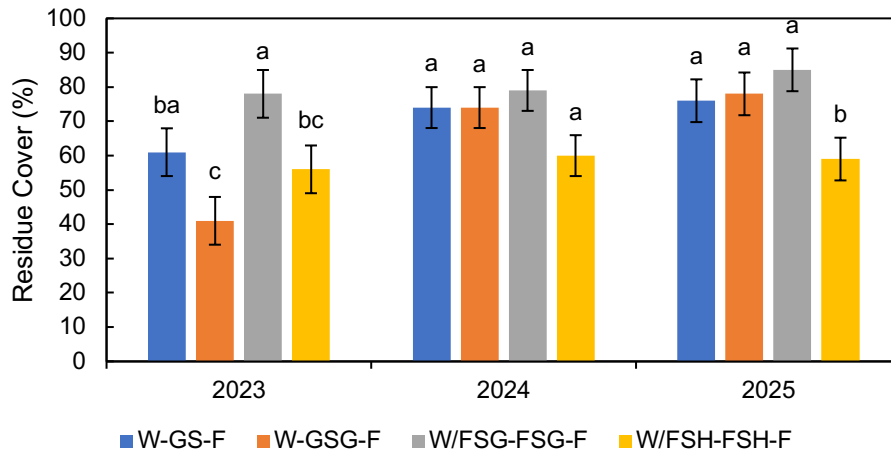


Figure 1. Intensification of W-GS-F with grazing, haying, and forage sorghum effects on residue cover. Means with the same letter within a year are not significantly different ($P \leq 0.1$).

Soil Organic Carbon and Aggregate Associated Carbon

Despite the differences in RC, bulk SOC was not significantly different among treatments in 2023 and 2024. In 2025, though minimal, W-GSG-F (1.02%) had significantly less bulk SOC than W-GS-F (1.12%), W/FSH-FSH-F (1.09%), and W/FSG-FSG-F (1.08%) treatments. Water stable aggregate-associated carbon at the 0-2-in depth showed no significant differences among treatments. However, treatments differed significantly in dry aggregate-associated carbon in nearly all three size classes. Grazed treatments (W-GSG-F and W/FSG-FSG) ranked first or second in SOC in all aggregate size classes compared to W-GS-F and W/FSH-FSH-F (Fig. 2).

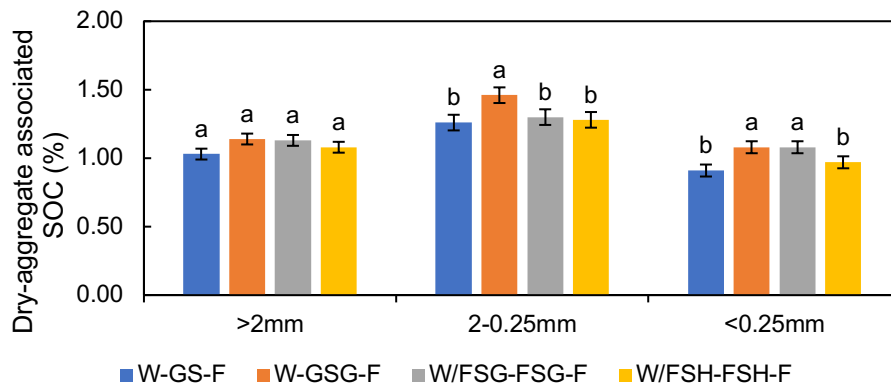


Figure 2. Intensification of W-GS-F with grazing, haying, and forage sorghum effects on dry-aggregate associated SOC. Means with the same letter within a size class are not significantly different ($P \leq 0.1$).

Nitrogen and Phosphorus

When averaged across the 0-6-in depth, no treatment differences were observed for soil N and P concentrations.

Aggregate Analysis

Wet aggregate MWD did not differ among treatments at the 0-2-in depth. Treatments W-GS-F (6.04 mm), W/FSG-FSG-F (5.62 mm), and W-GSG-F (5.59 mm) had similar dry-aggregate MWD, but W/FSH-FSH-F (4.99 mm) had significantly smaller dry-aggregate MWD compared to other treatments due to minimal soil RC. Therefore, W/FSH-FSH-F consistently exhibited greater percent wind erodible fraction (WEF) in all sampling years (Fig. 3).

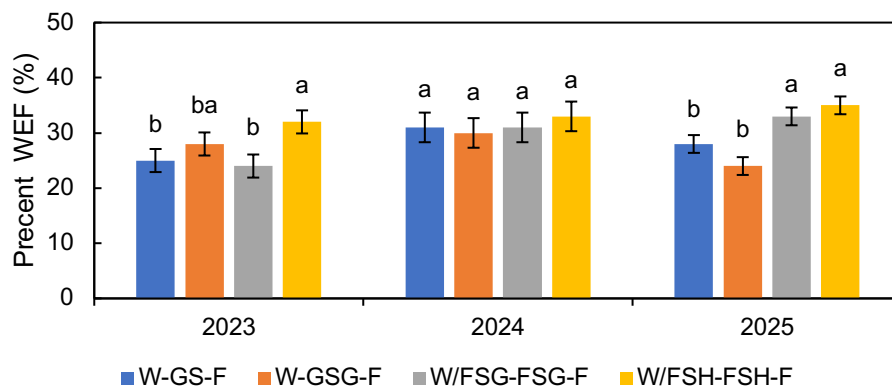


Figure 3. Intensification of W-GS-F with grazing, haying, and forage sorghum effects on dry-aggregate associated SOC. Means with the same letter within a year are not significantly different ($P \leq 0.1$).

Measures of Soil Compaction

Bulk density did not differ among treatments averaged across the 0-6-in depth. However, averaged across years, PR was significantly higher in the less-intensive cropping systems W-GS-F (0.73 MPa) and W-GSG-F (0.73 MPa), than W/FSG-FSG-F (0.63 MPa) and W/FSH-FSH-F (0.64 MPa).

System Net Returns

Averaged across 2024 and 2025, the net returns of grazed treatments (W-GSG-F and W/FSG-FSG-F) were greater than W-GS-F and W/FSH-FSH-F (Tab. 1). This is primarily due to high costs associated with baling, and low costs associated with forage for grazing.

Table 1. 2024 and 2025 average effect of rotation Intensification and haying and grazing on production net returns.

Management	Unit	W-GS-F	W-GSG-F	W/FSG-FSG-F	W/FSH-FSH-F
Total Revenue	\$/ac	484.37	598.74	503.61	569.93
Total Cost	\$/ac	389.88	391.30	356.63	509.31
Net Return	\$/ac	94.49cb	207.44a	146.98b	60.62c

Net Return means with the same letter are not significantly different ($P \leq 0.1$)

Conclusion

Intensification of W-GS-F with annual forages and grazing increased RC, and dry-aggregate SOC. Haying of annual forages diminished RC and dry-aggregate MWD, increasing percent WEF. Intensification with annual forages decreased PR, and had no significant effect on BD. Intensification and harvest type had no effect on bulk SOC, wet-aggregate SOC, N and P, and wet-aggregate MWD when compared to W-GS-F and W-GSG-F. The W-GSG-F treatment had the highest net returns, followed by W/FSG-FSG-F, then W-GS-F and W/FSH-FSH-F. Overall, grazing had positive or neutral impacts on soil health, while providing greater net returns.

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POST-WHEAT SUMMER COVER CROP EFFECTS CROP YIELDS, NET RETURNS, AND SOIL PROPERTIES IN A NO-TILL DRYLAND CROPPING SYSTEM

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ABSTRACT

Warm-season cover crops (CCs) planted immediately after wheat harvest in the semi-arid central Great Plains (CGP) could intensify cropping systems, increase forage availability, and enhance soil health in no-till (NT) dryland cropping systems. However, the costs of their establishment and potential reductions in subsequent grain yields due to reduced plant-available water present significant barriers to their adoption. This study was conducted from 2016 to 2023 near Brownell, KS, to determine post-wheat CC effects on available forage, grain sorghum yields, net returns, as well as soil properties. The CCs were grown post-wheat in an NT winter wheat (*Triticum aestivum* L.)-grain sorghum-fallow cropping system and either hayed, grazed, or left standing in a split-plot randomized complete block with four replications. Across years, post-wheat CCs produced about 2850 lb ac⁻¹ available forage, though production was highly variable. Grazing retained about 60% of the available forage as surface residue, while haying retained only about 20%. Grain sorghum yields were reduced 14% on average following CCs compared to fallow. However, average net returns with grazed or hayed CCs were similar to fallow and greater than standing CCs. Most soil properties were unaffected by fallow management, but grazed CCs increased soil organic carbon stocks compared to fallow. Mean weight diameter of water stable aggregates with grazed CCs was similar to fallow and greater than hayed CCs. These results suggest that post-wheat CCs for grazing and haying can intensify cropping systems and increase forage availability while maintaining profitability in the semi-arid CGP.

INTRODUCTION

Incorporating CCs to replace portions of the fallow periods in dryland cropping systems of the semi-arid CGP could regenerate soils, suppress weeds, and increase precipitation use efficiency (Obour et al., 2021). Warm-season CCs could be planted immediately after wheat harvest and terminated by killing-frost in October (Holman et al., 2023). However, little has been reported about post-wheat CCs in the semi-arid CGP. The costs of their establishment and potential reductions in subsequent grain yields due to reduced plant-available water at planting are significant barriers to their adoption (Obour et al., 2021). Despite this, dual-purpose CCs used for forage may have greater potential to balance profitability and soil health goals in such water-limited environments.

In semi-arid western Kansas, Holman et al. (2023) showed that post-wheat forage sorghum produced about 3500 kg ha⁻¹ aboveground biomass on average but reduced subsequent grain sorghum yields by 35% compared to fallow. Nevertheless, net returns were similar between these two rotations (Holman et al., 2023). However, how soil health is affected by management strategies like grazing or haying dual-purpose CCs in NT dryland cropping systems of the semi-arid CGP is not yet fully

understood (Simon et al., 2021; 2022). Past research suggested that dual-purpose CCs grown in place of fallow ahead of wheat had similar effects on soil properties as unharvested CCs (Simon et al., 2021). The objectives of this current research were to determine the impact of post-wheat CCs on available forage, grain sorghum yields, net returns, as well as soil chemical and physical properties.

MATERIALS AND METHODS

This study was conducted from 2016 to 2023 at the KSU HB Ranch near Brownell, KS (22 in average annual precipitation), to investigate best management strategies for CCs to replace fallow in the NT wheat-sorghum-fallow (WSF) cropping system. The study design was a split-plot randomized complete block with four replications. Crop phase was the main plot, and split-plots compared CCs grown post-wheat, managed as standing cover, hayed, or grazed, with chemically controlled NT fallow, for a total of four treatments. Split-plots were 9.1 m wide and 30.5 m long.

Immediately after wheat harvest, a CC mixture of forage sorghum, pearl millet (*Cenchrus americanus* (L.) Morrone), cowpea (*Vigna unguiculata* (L.) Walp.), and sunn hemp (*Crotalaria juncea* L.) was planted at a seeding rate of 7, 2.5, 20, and 5 lb ac⁻¹, respectively, using an NT drill. Grazing generally coincided with grass species heading stage and was facilitated using yearling heifers at densities from 782 to 1,565 lb liveweight ac⁻¹ for 4–7 d in fenced paddocks across the four replications of this study. Each year before grazing was initiated, CC biomass was determined by hand-clipping two areas of 5.4 ft² per plot. Samples were dried at approximately 122°F for a minimum of 48 h in a forced-air oven and weighed to determine dry matter. After grazing, each plot was resampled as previously described. Within one week following the last day of grazing, hayed CCs were harvested at a 6-in cutting height using a Carter small plot forage harvester from a strip of 3 ft by 100 ft in the middle of each plot. Whole plot fresh weights were recorded, subsamples collected and weighed, and then oven-dried to determine CC hay yield. The remaining plot area in the hayed plots was harvested after a sample strip was cut. Warm-season CCs were terminated by killing frost, generally near the third week of October.

Each year, winter wheat was planted in the 1st week of October using an NT drill and harvested in early July using a Massey Ferguson 8XP small plot combine harvester. Grain sorghum was planted in the 1st week of June using the same NT drill as used for wheat. Grain sorghum was harvested from mid-October to the 1st week of November using the same small-plot combine harvester as used for wheat. Net returns were calculated for the fallow/CC and subsequent grain sorghum phases of the WSF cropping system as total fallow/CC and grain sorghum revenue minus total fallow/CC and grain sorghum costs for each treatment and year. Estimates of current field operations and input costs used 5-year average custom rate values published by the Kansas State University Land Use Survey Program and the Kansas Department of Agriculture. Five-year average grain sorghum and CC hay prices were taken from the USDA Economic Research Services market reports (USDA ERS, 2021). Cover crop grazing lease rates were estimated using carrying capacity and a grazing lease price based on values published by Iowa State University Ag Decision Maker (Hofstrand & Edwards, 2015). Total variable costs were calculated as the sum of expenses for

fertilizer products and application, herbicide products and application, seed, planting, grain harvesting, and forage swathing and baling.

Soil samples were measured in the field from all plots in summer 2021. Two intact soil cores were randomly taken from the 0-2 and 2-6 in depths. Samples were dried separately at 221°F for 48 hr, and bulk density (BD) was determined as the mass of oven-dry soil divided by the core volume. Additionally, 10 soil cores were randomly collected within each plot, divided into the 0-2 and 2-6 in depths, air-dried, crushed, and sieved to pass through a 2 mm stainless steel screen. A portion of the 2 mm sieved samples was ground with a mortar and pestle to pass through a 0.25 mm sieve, and SOC concentration was determined by dry combustion after pretreating samples with 10% (v/v) HCl to remove carbonates. Carbon mass was calculated by multiplying SOC concentrations by soil BD and the thickness of the soil layer. Soil nitrate-nitrogen (NO₃-N) concentrations in samples were determined colorimetrically after extraction with 2 M KCl. Available phosphorus (P) was determined by the Mehlich-3 extraction method. Lastly, 5 intact soil samples were carefully collected from the 0-2 and 2-6 soil depths with a flat shovel for the determination of the mean weight diameter (MWD) of water-stable aggregates by the wet-sieving method and the wind-erodible fraction (WEF) (<0.84 mm) by the dry-sieving method.

Analyses of CC biomass accumulation, grain sorghum yields, net returns, and soil properties were conducted using the PROC GLIMMIX procedure in SAS ver. 9.4 (SAS Institute, 2012). For CC biomass, grain yield, and net returns, treatment and year were modeled as fixed effects, with replication treated as random. For BD, SOC, NO₃-N, P, MWD, and WEF, treatment and soil depth were modeled as fixed effects, with replication treated as random. Treatment effects were considered significant at ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Despite substantial research attention to replacing fallow before wheat, little information is available on fallow replacement after wheat harvest. Cover crops after wheat could intensify cropping systems and increase forage availability during a time of year when traditional forage resources are limited in the semi-arid CGP (Holman et al., 2023). Post-wheat CCs produced about 2850 lb ac⁻¹ total biomass on average (Fig. 1). Cover crop biomass accumulation was variable over the study period, with the most significant biomass production in 2016 and 2018 and relatively less in 2019 and 2020. Cover crops failed to establish in 2017 and 2021, and because of limited biomass production in 2019, CCs were not grazed or hayed. On average, aboveground biomass remaining post-grazing was 64% of pre-grazing biomass, which was consistent across years (Fig. 1). However, haying removed 80% of the pre-grazing CC biomass, which was representative of the total biomass present and available for forage. This indicates that haying likely retained only 20% of the aboveground CC biomass as residue. Planting warm-season CCs immediately after wheat harvest to take advantage of soil PAW near the soil surface will improve CC germination and emergence. When planting is delayed, the soil surface may dry, creating a poor environment for crop establishment without timely rainfall, which is unreliable in the semi-arid CGP.

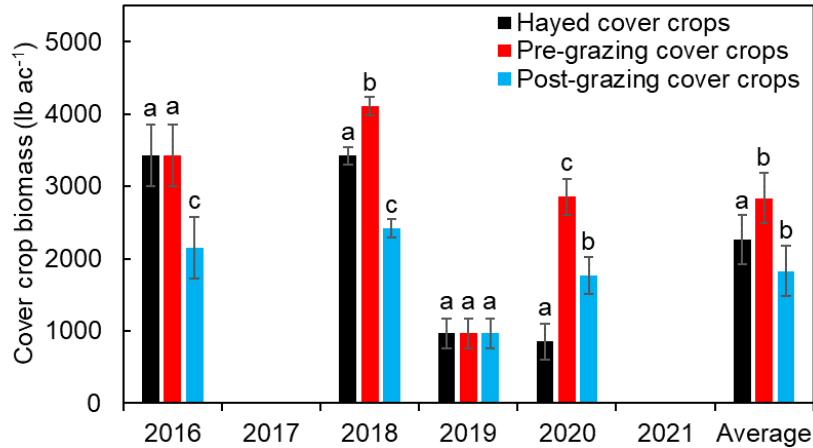


Figure 1. Cover crop biomass from 2016 to 2021 near Brownell, KS. Exceptional drought conditions in 2017 and 2021 resulted in crop failures. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

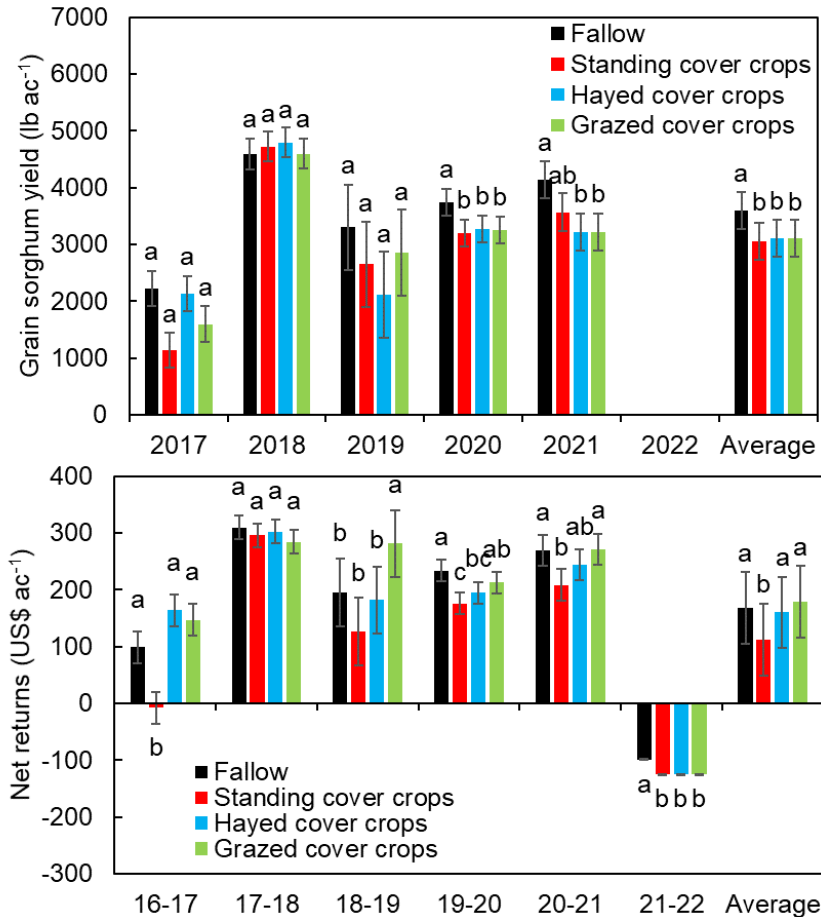


Figure 2. Post-wheat cover crop management effects on subsequent grain sorghum yields and net returns from 2017 to 2022 near Brownell, KS. Exceptional drought conditions in 2022 resulted in crop failures. Means followed by the same lower-case letter are not significantly different ($\alpha = 0.05$) among cover crop management treatments and bars indicate one standard error of the mean.

In semi-arid environments like the CGP, growing-season precipitation alone is not sufficient for stable grain production and is supplemented by PAW stored in soil during fallow periods (Obour et al., 2021). Cover crops reduced subsequent grain sorghum yields by about 14% compared to fallow on average (Fig. 2a). However, fallow management effects varied across years. Grain sorghum yields were unaffected by fallow management in 2017 and 2018. However, CCs reduced grain sorghum yields by 23% and 13% compared to fallow in 2019 and 2020, respectively (Fig. 2a). Interestingly, in 2021, grain sorghum yields were 22% less following hayed or grazed CCs compared to fallow, but standing CCs were not significantly different from fallow. Exceptional drought conditions resulted in a failed grain sorghum crop in 2022. Average net returns with grazed and hayed CCs were similar to fallow and greater than standing CCs (Fig. 2b). Returns with grazed CCs and hayed CCs were similar to fallow in most years except 2018-2019, when grazed CCs netted more than fallow, and 2021-2022, when fallow netted more than grazed or hayed CCs. Fallow had greater net returns than standing CCs in most years except 2017-2018 (Fig. 2b). A significant cost associated with CCs is the seed for planting, and the CC mixture used in the present study was a four-species diverse mixture. Others reported increased expense with broadleaf CC seed but limited biomass production (Holman, 2022). Simple grass-dominated CCs may increase net returns by reducing seed costs and increasing biomass production.

Table 3. Post-wheat cover crop management effects on bulk density (BD), soil organic carbon (SOC), nitrate-N (NO₃-N), phosphorus (P), mean weight diameter (MWD) of water stable aggregates, and wind-erodible fraction (WEF) in the 0-2 and 2-6 in soil depths in summer 2021 near Brownell, KS.

Management	BD	SOC	NO ₃ -N	P	MWD	WEF
	g cm ⁻³	ton ac ⁻¹	ppm	ppm	mm	%
0-2 in						
Fallow	1.17a [†]	3.51bc	21.65a	17.76a	0.84a	34.0a
Standing cover crops	1.14a	3.41c	21.66a	15.31a	0.65ab	31.8a
Hayed cover crops	1.21a	3.75ab	21.18a	17.74a	0.59b	35.9a
Grazed cover crops	1.22a	3.89a	23.29a	19.55a	0.84a	34.3a
2-6 in						
Fallow	1.43a	7.09b	6.44a	11.45a	0.59a	16.8a
Standing cover crops	1.40a	6.87b	6.04a	9.32a	0.69a	19.7a
Hayed cover crops	1.39a	6.87b	5.55a	10.65a	0.66a	16.3a
Grazed cover crops	1.43a	7.63a	7.23a	19.51a	0.88a	15.1a

[†]Means followed by the same lower-case letter within the same column are not significantly different ($\alpha = 0.05$) among treatments.

Despite the economic benefits of grazing or haying CCs, concerns remain that removing CC biomass through grazing or haying could limit the beneficial effects of CCs on soil health (Obour et al., 2021). Soil BD, NO₃-N, and P concentrations, and WEF were unaffected by fallow management treatments in the 0-2 or 2-6 in soil depths (Table 1). However, SOC stocks were greater with grazed CCs compared to fallow or standing

CCs in the 0-2 and 2-6 in soil depths. In the 0-2 in soil depth, SOC stocks with hayed CCs were greater than standing CCs but similar to fallow, which was similar to standing CCs (Table 1). In the 2-6 in soil depth, SOC stocks with hayed and standing CCs were similar to fallow, and all were less than those of grazed CCs. In the 0-2 in soil depth, MWD with grazed CCs was similar to fallow and standing CCs but greater than hayed CCs. The MWD in the 2-6 in soil depth was unaffected by fallow management. Based on the findings of the present study, we propose careful management to maintain adequate CC residue when using CCs for forage to meet soil conservation goals.

CONCLUSION

Results from this six-year study showed that post-wheat CCs produced about 2850 lb ac⁻¹ of total biomass on average. Still, biomass production was variable, with a significant risk of failed stand establishment. Grazing maintained about 60% of the available forage while haying maintained only about 20%. Grain sorghum yields were reduced 14% following CCs compared to fallow. However, average net returns with grazed or hayed CCs were similar to fallow and greater than standing CCs. Bulk density, NO₃-N, P, and WEF were unaffected by fallow management, but grazed CCs increased SOC stocks compared to fallow. This finding suggests a possible synergistic effect of CCs and grazing on SOC stocks. Mean weight diameter of water stable aggregates with grazed CCs was similar to fallow and greater than hayed CCs. These results suggest that integrating post-wheat CCs for grazing and haying into NT dryland cropping systems in the semi-arid CGP can intensify cropping systems and increase forage availability while maintaining profitability and soil health.

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AMELIORATION OF WATER REPELLANT SOILS AND IMPROVING THE PRODUCTION OF CALCAREOUS SOILS IN SOUTH AUSTRALIA – A FARMER EXPERIENCE

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We farm 18,000 acres of grain at Lock which is on central Eyre Peninsula in South Australia. The crops grown are wheat, lentils, barley and canola.

The climate is semi-arid and Mediterranean with hot dry summers and cool damp winters. The crops are grown through the winter and spring period with planting in May and harvest beginning in November at the beginning of summer. Frost is uncommon but does occur and although the rainfall is low it is relatively reliable. There is some risk of frost damage at flowering, and that risk decreases further into spring, however the risk of heat damage during flowering and grain fill increases further into spring.

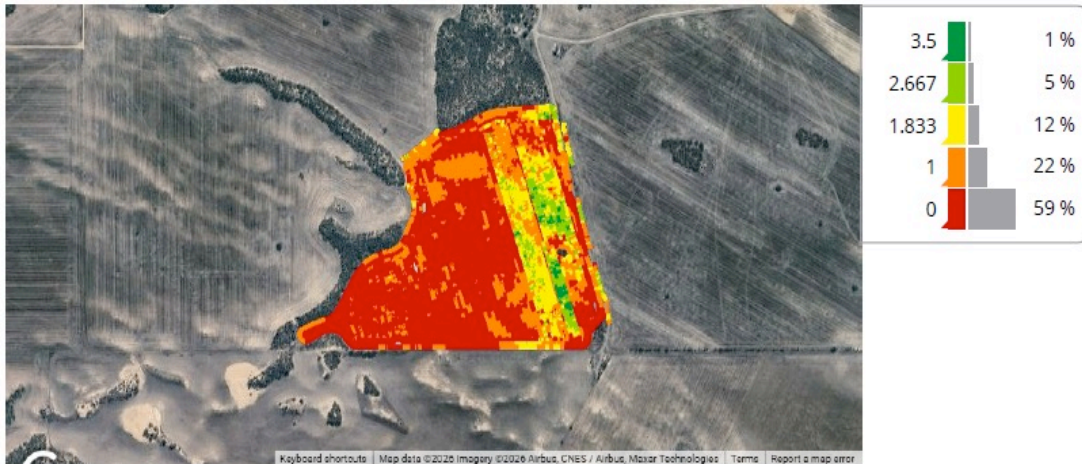
Crops are established with full residue retention and zero tillage. Crops are grown in a dryland farming system where annual rainfall is 350 mm (13.75 inches) and ranges from 200mm (8 inches) through to 420mm (16.8 inches). July is the wettest month and the rainfall decreases either side of July and January is the driest month. May is when the seasonal break from the summer dry period usually occurs.

The soils are duplex sands over clay and other areas of calcareous sands with high pH and with some surface limestone. The duplex sands tend to be water repellent which often means poor crop establishment and reduced yields. The pH of the duplex soil is around 6.5 - 7.0 at the surface and the clay is higher pH, often up to 8.0. In the calcareous soil the pH is 8.4 – 8.7 at the surface and increases with depth, often up to 9.5. There can be up to 50% free lime in the calcareous soils.

We have developed various techniques and machinery to overcome the limitations of these soils and in most instances are able to immediately almost double yields. The techniques include using a machine to delve clay up from below the sand, mix the clay and sand and plant the crop. This is achieved all in one pass of the machinery. Once these soils are ameliorated in this manner they can be farmed in our normal way for at least ten years before a repeat treatment may be necessary. We also use soil wetters applied in the furrow at planting on fields that have not yet been ameliorated to address immediate crop establishment issues. There are other techniques used such as clay spreading and incorporation, some deep ripping, but most involve the mixing of clay with the sand in some form.

When planting crops into water repellent sand, germination is staggered and uneven, plant populations are often low. The delayed germination reduces the length of the growing season and so reduces yield.

This yield map below shows the motivation for carrying out the amelioration. It also shows the changes in soil type from the parallel dune swale system where there are duplex soils on the dunes and then the random calcareous dunes towards the bottom of the picture.



Duplex sand over clay



Water Repellent Sand



Two examples of ameliorated soil production alongside non ameliorated soil



The spader used for ameliorating the soil. The front view shows the clay delving tynes that lift the clay to the surface, followed by the mixing action of the spader and then the seeder to place the seed and fertiliser, with the press wheels to firm the seedbed and assist with germination.



The wheat on the left has been established with the spader. (Mohawk on the left, Scepter on the right)

Calcareous Soils

Australian soils have a low phosphorus (P) status compared with soils in the United States or Europe (Donald 1964). According to the recent National Land and Water Audit, there are over 76 million ha of alkaline soils (soils with $\text{pH}_{\text{CaCl}_2} > 7.0$), with the major portion of the area situated in SA, Victoria, WA and parts of NSW and Queensland (Figure 2).

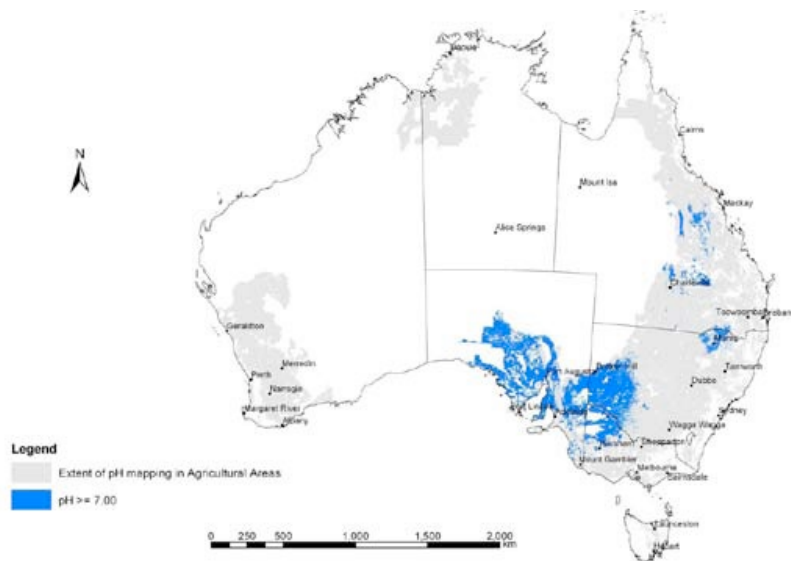


Figure 2. Alkaline soils predominate in the arable regions of SA, south-western NSW and north-western Victoria.

These soils are usually in low to medium rainfall environments with moderate potential grain yields, and fertiliser input costs are a critical component of farm productivity. In the northern and western part of Eyre Peninsula in SA, arable calcareous soils (5-90% calcium carbonate (CaCO_3)) cover an area greater than 1 million ha and produce 10% of the South Australian wheat crop.

Wheat growth on these soils is often poor, particularly in the early stages following emergence when P requirement is critical.

The major chemical constraints for agricultural productivity associated with alkaline soils under the dryland climate of southern Australia include low P and nitrogen (N) availability, micronutrient (zinc - (Zn) manganese, - (Mn), copper - (Cu), and iron - (Fe) deficiencies, and/or toxicities (e.g. excessive boron (B), sodicity, salinity).

Granular P fertilisers have been used for more than 100 years in southern Australia. However, responses of wheat to increasing rates of granular P-fertiliser are very low on highly calcareous soils. Wheat plants are also commonly deficient in Zn, Mn, and sometimes Cu on alkaline soils. Fertilisers constitute the largest on-farm variable cost, yet efficiency of nutrient uptake is still inadequate. The technology has not advanced meaningfully in 50 years. In a survey of key research issues for

growers on Eyre Peninsula in 2000, crop nutrition and soils were identified as the top two research issues needed to improve productivity.

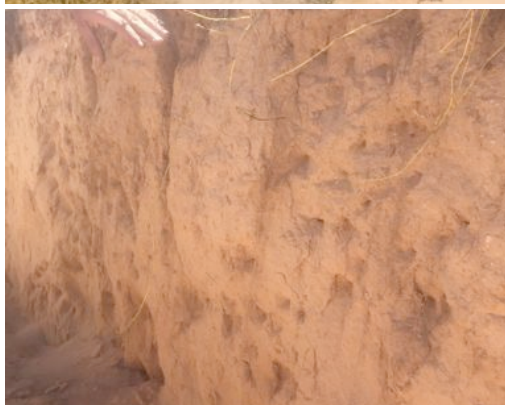
Over the past decade new research using advanced spectroscopic techniques has shown that concentrated P salts in granular fertiliser attract soil water, which in calcareous soils, contains high concentrations of calcium, (Ca) (Figure 6).

The Ca combines rapidly with P, precipitating it as insoluble phosphates which are no longer readily available to plant roots (Figure 6 b & c). This is why the traditional way of providing P to crops on calcareous soils, using granular fertiliser, has not been as effective as it should be.

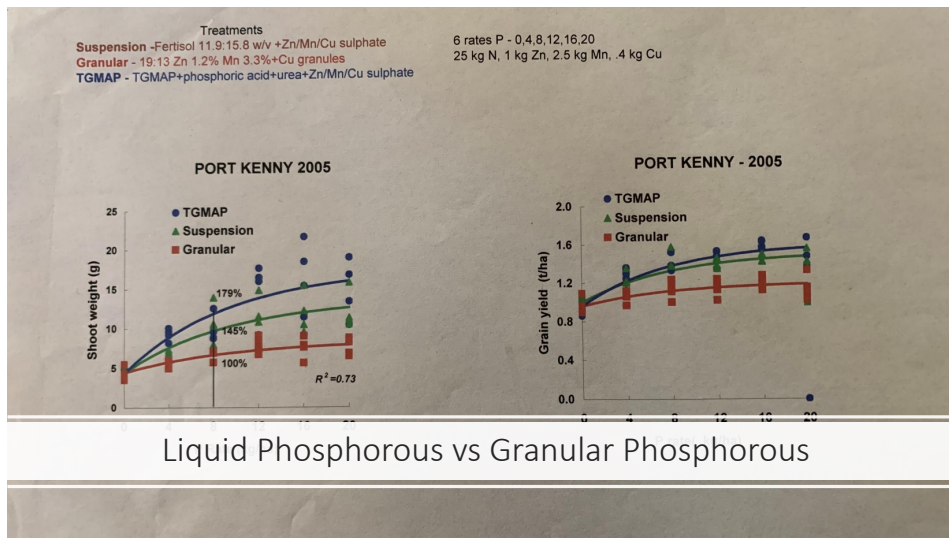
(Source: Fluid Fertilisers: A South Australian Manual

Project Leader: Prof. Michael McLaughlin, Soil and Land Systems, School of Earth and Environmental Sciences,

CSIRO Land and Water and University of Adelaide)



Calcareous soil profile



(R. E. Holloway et al)

Note both the dry matter response and the yield response to the P applied in the liquid form compared to the granular application.



Granular Phosphorous

Fluid Phosphorous

Bertrand et al. 2006: Nutr. Cycl. Agroecosys. 74: 27-40 • Plants took up 22% more P from liquid fertilisers in grey calcareous soils.

We have been using liquid phosphorous at seeding applied in the seed row and below the seed since 2003. Many of the initial trials were done on our place and while the yield gains ranged from a 7% to a 38% percent improvement over using granular fertiliser the change has given about a 19% yield improvement on average. This has been one of the most worthwhile changes in technology for our farm. Phosphoric acid has been our main source of phosphorous, but in more recent years we have changed to mostly using ammonium poly phosphate which is a much safer product for staff to handle and is easier on equipment. The phosphoric acid has the advantage of being able to mix in good rates of sulphate trace elements of zinc, copper and manganese.



The blue and red liquid lines carry fertilizer and the yellow line soil wetter.

Phosphorous is applied at 12 (elemental P) kilograms per hectare (24.5 lbs/acre P_2O_5). There is usually some urea ammonium nitrate and trace elements added at the same time in a separate stream. The total liquid applied is 70 litres/hectare (7.5 US gallons per acre). Seeding is carried out with an 18 metre (60ft) seeder covering about 16 hectares/hour (40 acres/hr). Section control is used.

In the future we will apply a range of phosphorous rates across the field and the crop will be yield mapped to determine the response in varying soil types. Average field size is around 240 hectares (600 acres), so there can be significant variation across a field. Then variable rate application maps will be constructed to apply the optimum economic rate of fertilizer according to soil type and yield response.

Summary

In the Australian environment it is possible to lift yields and therefore profit very significantly by targeted soil amelioration and soil fertility amendment in non-wetting soils.

On calcareous soils in the low rainfall environments there are good responses to using fluid phosphorous instead of granular phosphorous and the increased dry matter production assists in extra microbial activity and carbon cycling which improves nutrient availability.

EVALUATING THE PROFITABILITY OF NITROGEN MANAGEMENT STRATEGIES TO INCREASE YIELD IN REGENERATIVE COTTON PRODUCTION SYSTEMS

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ABSTRACT

The objective of this study was to conduct an economic analysis of field trials conducted in 2018, 2019, and 2020 at the Agricultural Complex for Advanced Research and Extension Systems in Lamesa, TX, USA. The trials evaluated the impact of four nitrogen (N) fertilization timings on cotton yield: Farmer Practice (FP), FP + an additional application of N before planting (PRE), FP + an additional application of N post-emergence (POST), and FP + an additional application of N after pinhead square (PIN). Trials were conducted in a rye cover-crop system and in a conventional tillage system with winter fallow. In trials, an early-season N application resulted in a statistically significant increase in cotton yields in the cover-crop system but did not affect yields in the conventional system. To evaluate the relative profitability of different nitrogen timings in the cover crop system, we developed economic budgets and compared gross margins across nitrogen timings. Based on our results, an additional application of N before planting increased gross margin by \$74/acre relative to Farmer Practice. An additional application of N post-emergence increased gross margin by \$89/acre relative to Farmer Practice.

SPATIAL AND TEMPORAL VARIABILITY OF NITROGEN RESPONSE IN GRAIN SORGHUM

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ABSTRACT

Nitrogen (N) response in grain sorghum is spatially and temporally variable, complicating estimation of optimum N rates and limiting the effectiveness of uniform fertilizer recommendations. This study evaluated within-field and year-to-year variability in N response using block-level response modeling and soil variability analysis. Field experiments were conducted in Stillwater, Oklahoma, during the 2024 and 2025 growing seasons using six N fertilizer rates (0, 39, 79, 118, 157, and 196 kg N ha⁻¹). Yield response curves were fitted at the block level and classified into response types, and soil physical and chemical properties were summarized using interquartile range (IQR) analysis. Nitrogen responsiveness differed substantially between years, with lower and more variable optimum N rates and yield potential observed in 2024 compared with 2025. The relationship between optimum N rate and yield potential was not significant in either year, indicating that N_{opt} alone did not explain yield variability. Soil texture, salinity, aggregate stability, and penetration resistance differed among N response classes, highlighting the role of within-field soil variability in shaping N response behavior. These results demonstrate that classifying N response by response type, combined with spatial and soil variability analysis, provides additional insight beyond optimum N rate alone and supports the development of site-specific nitrogen management strategies.

OPTIMIZING NITROGEN INPUTS IN BARLEY PRODUCTION IN IDAHO, MONTANA, AND NORTH DAKOTA

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ABSTRACT

Nitrogen (N) management plays a critical role in balancing grain yield and malting quality of two-row spring barley (*Hordeum vulgare* L.) grown in the Northern Plains and Intermountain West. Field experiments were conducted at six locations across North Dakota, Montana, and Idaho to evaluate the effect of N fertilizer source on grain yield, protein, and kernel plump. Treatments included commercially available N sources, including enhanced-efficiency urea, urea ammonium nitrate, calcium ammonium nitrate, sulfur enriched granular urea, a non-fertilized check, and others sources, with all fertilized treatments applied at 80% of the regional recommended N rate for malting barley production. Treatments were arranged in a randomized complete block design. Nitrogen fertilization significantly increased grain yield compared with the unfertilized treatment in all states, whereas kernel plumpness was not affected by N sources in any state. Grain protein was influenced by N source in North Dakota, Montana, and Idaho, with small differences between sources. All treatments produced grain quality within the industry-required parameters.

INTRODUCTION

Barley (*Hordeum vulgare* L.) is an important cereal crop cultivated in the United States, used primarily for malting, food products, and animal feed. According to USDA Crop Explorer, in the 2025/26 crop year, global barley production is projected to reach roughly 147,35 million tons, with the United States contributing about 3.38 million tons.

Idaho, Montana, and North Dakota are the three highest barley-producing states in the country (USDA-NASS, 2025). Despite regional differences, barley plays a major economic role across these states. In 2024, 66.2% of the barley planted in Montana was malt varieties (USDA-NASS, 2024), while approximately 90% of North Dakota production is contracted specifically for malting markets (North Dakota Barley Council, 2025), while Idaho is about 70% (Idaho Farm Bureau, 2025). Barley destined for malt receives a price premium and is accepted only when strict quality specifications are met (North Dakota Barley Council, 2025; MacLeod, 2014). According to the American Malting Barley Association (AMBA), acceptable malting barley requires protein concentrations below 13% and kernel plumpness above 90%, because lower protein concentrations allow kernels to reach the desired moisture content faster, accelerating the malting process (Hertsgaard et al., 2008; AMBA, 2025).

In barley, N is the most yield-limiting nutrient for barley (McFarland et al., 2015) and also has a strong influence on and grain quality. Adequate N is essential for

maximizing yield; however, excessive N supply can increase grain protein concentration above malting thresholds and lower kernel plumpness (Franzen, 2023; Goettl et al., 2024; Sainju et al., 2024). To improve N use efficiency and minimize environmental losses, enhanced-efficiency fertilizers (EEFs), including urease and nitrification inhibitor-treated urea and controlled-release formulations, have been developed to synchronize N availability with crop uptake (Franzen, 2022).

With so many available commercial N fertilizers and the agronomic and environmental challenges associated with N management, this research highlights the need for region-specific N strategies for malting barley across the major producing areas of the Northern Great Plains and Intermountain West. Given the importance of maintaining malting quality while sustaining yield and reducing environmental losses, this study addresses these needs by evaluating how N fertilizer source affects grain yield, protein, and kernel plumpness in two-row spring barley grown across Idaho, Montana and North Dakota.

MATERIALS AND METHODS

Six field experiments were conducted during the 2025 growing season across Idaho, Montana and North Dakota. These sites represent distinct soil types; Idaho: Bahem (silty loam) and Declo (loam); Montana: Swims (silty clay); North Dakota: Fargo-Hegne (silty clay), Hamerly-Wyard (loam), and Barnes-Buse (loam) (Soil Survey Staff, 2025). Idaho trials were located near Aberdeen and Kimberly. Montana, one field trial was established near Kalispell. In North Dakota, trials were located near Hillsboro, Lakota, and Valley City.

The experiments were arranged in a randomized complete block design (RCBD) with five N treatments with four replicated blocks in Idaho, nine N treatments with three replicated blocks in Montana, and nine N treatments with four replicated blocks in North Dakota. Treatments consisted commercial N fertilizer sources, each applied at 80% of the respective state's recommended rate, and one unfertilized check. N application rates were determined based on state-specific recommendations. For Idaho sites, the amount of N was calculated following University of Idaho recommendations at 178 lb N ac⁻¹ (Mahler & Guy, 2007). For Montana, the crop demand was calculated according to Montana State University recommendations at 96 lb N ac⁻¹ (Dinkins & Jones, 2019). In North Dakota, the total known available N was calculated according to North Dakota State University recommendations at 150 lb N ac (Goettl et al., 2024). Each fertilizer source had distinct chemical characteristics and release mechanisms (Table 1). Prior to planting, composite soil samples were collected from each site to determine baseline fertility, including nitrate-N (0-24 in), phosphorus (P), potassium (K), pH, and organic matter (0-6 in). Barley cultivars AAC Synergy (planted at two sites in North Dakota and one in Montana), Explorer (planted at one site in North Dakota), and BC Lexy, Copeland, LCS Odyssey, and Moravian 179 (planted in Idaho) were used—all two-row cultivars recognized by AMBA for malting quality potential (AMBA, 2025).

Table 1. Descriptions of various nitrogen fertilizer sources.

Source	N	Description
Amidas	40%	Urea with ammonium, and sulfur (Yara)
Ammonium Nitrate	33%	Fertilizer supplying nitrogen in both ammonium and nitrate forms
Ammonium Sulfate	21%	Nitrogen in the ammonium form with sulfur as sulfate
CAN27	27%	Nitrate and ammonium forms of N with added calcium (Yara)
ESN	44%	Polymer-coated urea (Nutrien)
Pivot Bio RETURN + Urea	46%	Nitrogen-fixing microbes (Pivot Bio)
SSN Urea	46%	Urea coated with Maleic Itaconic Copolymer (Simplot)
Nutrisphere-N	46%	Urea with both a urease inhibitor (NBPT) and a nitrification inhibitor (DCD) (Koch Industries)
SuperU	46%	Urea with both a urease inhibitor (NBPT) and a nitrification inhibitor (DCD) (Koch Industries)
Tropicote*	15.50%	Calcium nitrate (Yara)
UAN	28%	Liquid urea and ammonium nitrate
Urea	46%	Granular fertilizer
Urea + NBPT	46%	Urea with urease inhibitor

To determine N rate for Idaho site, University of Idaho's recommendation was followed. Fertilized N needed was calculated as the sum of N needed based on potential yield, N needed for residue breakdown, less mineralizable N and N soil test (Mahler & Guy, 2007). Total N corresponded to 94 ± 22 lb N ac^{-1} for the unfertilized check treatment and 178 ± 32 lb N ac^{-1} for all fertilized treatments. For Montana site, Montana State University's recommendation was followed, and total crop N requirement was calculated using a fixed rate of 1.2 lb N ac^{-1} for each bushel per acre of expected barley yield, less the amount of soil nitrate-N measured before planting (Dinkins & Jones, 2019). Total N corresponded to 17 ± 2.7 lb N ac^{-1} for the unfertilized and 96 lb N/ac for all fertilized treatments. For North Dakota sites, the total known available N (TKAN) was calculated as the sum of soil nitrate (N_s), previous crop credit (N_{pc}), tillage contribution (N_t), and fertilizer N applied (N_{fert}), following the NDSU recommendation framework (Franzen, 2023). For this experiment, TKAN levels corresponded to 87 ± 16 lb N ac^{-1} for the unfertilized check and 150 lb N ac^{-1} for all fertilized treatments.

All fertilizers were surface applied within one week of seeding. Seeding occurred between April 15 and May 9, 2025. In-season crop management carried out by the cooperating farmers (North Dakota) or by university research staff at experimental stations (Montana and Idaho), in accordance with regional best management practices, to control pest and disease pressure. Harvest occurred between August 13 and September 4, 2025. Grain moisture and test weight were measured using a Dickey-John model GAC500 XT grain analyzer (Dickey-John, Auburn, Illinois) or a Tango II near-infrared analyzer (Bruker, Billerica, Massachusetts). Grain harvest weights were adjusted to the standard moisture content of 13.5% for yield calculations. Percent plump kernels were considered the weight of kernels which do not pass through a 6/64-inch sieve. Grain protein content was determined using near infrared spectroscopy (NIR).

Data analysis was performed using JMP (SAS Institute, Cary, NC). Analysis of variance (ANOVA) was carried out as randomized complete block design. Data in this study was considered statistically significant at $p \leq .05$.

RESULTS AND DISCUSSION

Grain Yield and Quality

Barley grain yield responded significantly to N source in Idaho, Montana, and North Dakota ($p < .05$; Table 2). In all three states, fertilized treatments produced significantly greater yields than the non-fertilized check. In Idaho, the highest yields were obtained with Urea+NBPT, SSN Urea Nutrisphere-N, and Ammonium sulfate, while the check treatment resulted in the lowest yield. In Montana, the highest yields were observed with Amidas, SuperU, Urea + NBPT, and Pivot Bio + Urea, while UAN produced lower yields among fertilized treatments. In North Dakota, yield differences were primarily associated with fertilization compared with the check treatment, and yields did not differ significantly among fertilized N sources. These results indicate that multiple N sources supplied sufficient plant-available N to maximize barley yield across locations.

Grain protein responded significantly to N source in Idaho, Montana and North Dakota ($p < .05$; Table 2). In Idaho, protein concentration ranged from 9.5 to 11.0% and in Montana from 9.3 to 10.9%, with mean separation showing small differences among N sources (Table 2). In North Dakota, the non-fertilized check had the lowest protein content (10%), whereas fertilized treatments generally resulted in higher protein concentrations (10.6-11.2%). Fertilized treatments remained within the acceptable threshold but trended toward the upper limit, indicating that N additions enhanced yield but also elevated grain protein concentration.

Kernel plump was not affected by N source in Idaho, Montana, or North Dakota (Table 2). Plumpness values remained uniformly above 94% for all sites, indicating that kernel filling was more strongly influenced by environmental conditions-such as temperature and moisture than by fertilizer source. Thus, while N management affected yield and protein, plumpness remained stable, underscoring that N source selection can optimize yield and protein without compromising kernel quality.

CONCLUSION

Nitrogen fertilization increased barley grain yield across Idaho, Montana, and North Dakota, while differences among fertilizer sources were minimal when applied at 80% of the recommended N rate. Grain protein increased with N fertilization but remained within acceptable limits for malting, and kernel plumpness was unaffected by N source. These results indicate multiple N fertilizer sources can be used to achieve high yield and maintain malting quality across diverse production environments. Without impacting malting quality, the cost and sustainability benefits of each fertilizer can be weighed independently to meet farm economic and sustainability goals.

Table 2. Mean values for barley yield, grain protein content, and kernel plump averaged across research sites in Idaho, North Dakota, and Montana.

State	Treatment	Yield	Protein	Plump
		bu ac ⁻¹	%	%
Idaho	Urea + NBPT	163 a	10.9 a	97.5
	SSN Urea Nutrisphere-N	152 a	10.5 a	98.8
	Ammonium Sulfate	152 a	10.4 ab	98.5
	SuperU	151 ab	10.3 ab	98.1
	ESN	150 ab	11.0 ab	98.6
	Can27	145 ab	10.8 ab	98.5
	Urea	144 ab	10.9 ab	98.5
	Ammonium Nitrate	141 ab	9.9 ab	98.3
	SuperU + ESN*	139 ab	10.9 ab	98.6
	Amidas	138 ab	9.5 ab	98
	Check	123 b	10.0 b	98.4
	<i>p</i> -value	<.05	<.05	NS
North Dakota	Urea	58.3 a	11.0 a	95.1
	Can 27	59.7 a	10.9 ab	94.9
	Amidas	58.5 a	11.2 a	94.4
	UAN 28	58.8 a	10.6 b	94.8
	SuperU	59.7 a	11.0 a	94.6
	Tropicote [†]	57.8 a	11.0 a	94.7
	Urea + NBPT	58.5 a	11.0 a	94.4
	ESN	53.5 ab	11.1 a	95.4
	Check	47.2 b	10.0 c	96.2
		<i>p</i> -value	<.0001	<.0001
Montana	Can 27	130 a	10.1 ab	98.5
	Amidas	140.07 a	10.9 a	98.5
	SuperU	139.64 a	10.8 a	98.1
	Urea + NBPT	135.19 a	10.6 a	98.7
	Pivot Bio + Urea	135.15 a	10.3 ab	98.6
	Urea	122.22 ab	10.0 ab	98.3
	ESN	121.26 abc	10.9 a	97.8
	UAN	102.54 bc	9.3 a	98.7
	Check	95.28 c	9.4 b	98.4
		<i>p</i> -value	<.05	<.05

Note: Means with the same letter within the same column for each state are not significantly different at the .05 probability level.

Abbreviations: NS, nonsignificant; ESN, Environmentally Smart Nitrogen; UAN Urea Ammonium Nitrate

*50% SuperU + 50% ESN

[†]10% Tropicote + 90% Urea

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EVALUATION OF NITROGEN FERTILIZER AND RHIZOBIUM INOCULATION TO IMPROVE GRAIN YIELD AND QUALITY OF SOYBEAN AND DRY BEAN IN EASTERN MONTANA

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ABSTRACT

Interest in production of irrigated soybean and dry bean in Eastern Montana's Lower Yellowstone River Valley increased substantially following the closure of a sugar beet processing facility in Sidney, MT resulting in the need for a replacement crop(s) on 30,000 to 40,000 acres annually. However, research-based information addressing appropriate agronomic practices for these crops is lacking, including nitrogen (N) fertility management. N management for legumes is complicated by their symbiotic N fixation with rhizobia, which is determined by the presence of crop specific rhizobia in the soil or introduced via commercial inoculants. The success of commercial inoculants can vary based on product selection, crop type and field cropping history. Furthermore, the addition of fertilizer N can have variable effects on the establishment and productivity of symbiotic N fixation. Understanding when commercial rhizobium inoculants are needed and what levels of N fertilizer applied at planting are beneficial is critical for successful production and profitability of these crops. To address these issues, a two-year study evaluating soybean and dry bean's response to rhizobium inoculation and N fertilization was conducted. Two cultivars each of soybean and dry bean were subjected to N fertilizer rates of 0, 6 and 56 kg N ha⁻¹ applied at planting. Each fertilizer rate was planted with and without rhizobium seed inoculation for a total of six treatments. Soybean seed yield and protein increased significantly with inoculation. Fertilization of soybean with 6 kg N ha⁻¹ did not affect yield, but fertilization at the high N rate partially reduced the benefits derived from inoculation in soybean. The response of dry beans to the same set of treatments differed considerably from soybeans. No positive response to inoculation was observed and a small decrease in seed yield was observed with the high N rate in one of the two years. The results of this study indicate that the two crops respond differently to rhizobium inoculation and that the addition of small to moderate rates of N fertilizer at planting provides little benefit in Eastern Montana.

INTRODUCTION

The N requirements of legumes can be met through uptake of mineral N from the soil or from fixation of atmospheric N derived from a symbiotic interaction with rhizobia bacteria. This symbiotic N fixation (SNF) is energy intensive requiring photosynthetically derived sugars from the plant. As a result, legumes are sensitive to soil mineral N levels and will limit SNF when N levels in the soil are high. The percentage of plant N derived from SNF varies depending upon plant species and location with estimates for soybean ranging from 44% to 78% and dry bean at 38% (8). N fertilization can reduce the percentage of SNF-derived N in the plant with estimates in soybean of 84% in unfertilized conditions and 34% following N fertilization at or above 84 kg N ha⁻¹ (5).

N fertilization recommendations for soybean and dry bean vary based on location and agricultural practices. Typically, N fertilization of soybeans is not recommended unless specific conditions exist that might result in a N deficiency in the crop. Studies evaluating the yield response of soybean to N fertilization observed yield increases of 8-32% following N application (7). However, variability in site- and year-specific environmental effects, management practices and N fertilization rates and methods generates inconsistent responses both within and across studies (7). As a result, it is difficult to draw broad conclusions regarding the response of soybean to N fertilizer. Dry bean N fertilization is a common practice in the Northern Plains with producers applying 56 kg N ha⁻¹ on average with recommendations for N application beginning when soil N levels fall below 56 kg ha⁻¹ (2). The dry bean response to N application varies across studies. Buetow et al. (2) reported no increase in seed yield at a rate of 56 kg N ha⁻¹ whereas Chekanai et al. (3) reported an increase in seed yield at 40 kg N ha⁻¹. Furthermore, Edje et al. (4) observed a seed yield response to N at 200 kg N ha⁻¹ but not at 40 to 160 kg N ha⁻¹. Finally, challenges associated with determining the need for N fertilization in soybean and dry bean are further confounded by the lack of consistent responses of each crop to rhizobium inoculation as well as a negative association between soil N levels and SNF (9,10). The objectives of this study were to 1) evaluate the response of soybean and dry bean to rhizobium inoculants in the Lower Yellowstone River Valley of Eastern MT and 2) examine the need for the additional N fertilizer at planting and assess what N rates are appropriate.

MATERIALS AND METHODS

A two-year study was conducted under sprinkler irrigation at the Eastern Agricultural Research Center in Sidney, MT in 2024 and 2025. The study site had no recent history (>10 years) of soybean or dry bean crops. The trials were preceded by spring wheat in both years with background soil nitrate levels (0-61 cm) of 39 kg ha⁻¹ in 2024 and 20 kg ha⁻¹ in 2025. Two cultivars of soybean (CP0337X and R0422XF), one pinto bean (Cowboy) and one red bean (Viper) were grown at three different fertilizer levels including 1) None (Control), 2) 6 kg N ha⁻¹ and 29 kg P₂O₅ ha⁻¹ (6N) and 3) 56 kg N ha⁻¹ and 29 kg P₂O₅ ha⁻¹ (56N). Each fertilizer level was planted with and without rhizobium seed inoculation (PrimoGX2 for soybean and N-Charge for dry bean, Verdesian Life Sciences, Cary, NC) for a total of six treatments. Soybean and dry bean were planted at 43 and 21 seeds per square meter with a row spacing of 46 cm. At the R3 development stage, plants from one row meter were dug from each plot. Nodulation scores were derived from three categories including plant growth and vigor, nodule color and number, and nodule position with scores of 0, 1, 3, or 5 assigned for each category and summed to give a total nodulation score. Above ground biomass was collected, dried and weighed following evaluation of nodulation. Grain was harvested at maturity and yields were adjusted to 13 percent moisture content. Soybean protein and oil were determined by near-infrared spectroscopy. Data were analyzed using R statistical software version 4.2.2 (R Foundation for Statistical Computing, Vienna, Austria). Linear mixed effects models were fit using the lmer function in the lme4 R package (version 1.1-35.3) (1) treating year, genotype and treatment as fixed effects and replicate as a random effect. Pairwise comparisons were performed in the emmeans (version 1.10.4) (6) R package using the Benjamini-Hochberg procedure for P-value adjustment.

RESULTS

The results of an analysis of variance (ANOVA) are presented in Table 1. Due to the presence of significant year interactions with all parameters except nodule score and seed oil, ANOVA were performed by each year for soybean genotype and treatment main effects. Soybean seed yield was significantly affected by genotype in 2024 but not 2025 with R0422XF outyielding CP0337X in 2024 (Fig. 1A and 1C). Treatment significantly affected soybean yield in both years (Fig. 1B and 1D) with the inoculated (Inoc) and inoculated plus 6 kg N ha⁻¹ (Inoc + 6N) treatments producing the highest yields. Yields for the three uninoculated treatments were lower than the inoculated treatments in both years. Soybean nodule scores were significantly affected by year and treatment but not genotype (Table 1). Nodule scores were higher in 2025 than 2024 (Fig. 1E). The Inoc and Inoc + 6N treatments also produced the highest nodulation scores (Fig. 1F). Nodulation scores for the inoculation plus 56 kg N ha⁻¹ (Inoc + 56N) treatment did not differ from the Control treatment (Fig. 1F).

Table 1. ANOVA table mean squares showing the effects of year, genotype, treatment and their interactions on seed yield, nodule score, biomass, seed protein and seed oil.

Source of Variation ^a	Seed Yield	Nodule Score	Biomass	Seed Protein	Seed Oil
Soybean					
Y	16535158***	160.2***	830.6**	18900***	125.6*
G	11446	2.7	41	5813***	71.8*
T	3236488***	169.8***	75.3*	3822.2***	424.3***
Y x G	786792**	11.1	15.7	438*	41.3
Y x T	231790*	1.4	265.4***	115.2	18.7
G x T	36926	0.7	27.6	56	11
Y x G x T	85105	1.8	22	85.8	8.5
Dry bean					
Y	37373677***	90.1**	574.1 **		
G	1109	73.5***	51.9		
T	185168*	21.8***	7.3		
Y x G	529409**	73.5***	0.4		
Y x T	181548*	3.9	34.6		
G x T	59550	15*	33.5		
Y x G x T	73488	3.6	25.2		

^a Year (Y), Genotype (G), Treatment (T)

*, **, *** Significance at the 0.05, 0.01 and 0.0001 probability levels

Soybean biomass was significantly affected by treatment (Table 1). The 56 kg N ha⁻¹ (56N) and Inoc + 56N treatments produced the least biomass in 2024 and the most in 2025 (Table 2). Soybean seed protein was significantly affected by both genotype

and treatment with R0422XF higher than CP0337X (Table 2). The Inoc and Inoc + 6N treatments produced the highest seed protein and the Control, 6N and 56N treatments the lowest. Soybean oil contents varied by year, genotype and treatment (Table 1). Year and genotype effects, although significant, were small and likely not biologically relevant (Table 2). Treatment effects on seed oil content were opposite that of protein with the three uninoculated treatments generating the highest oil contents (Table 2).

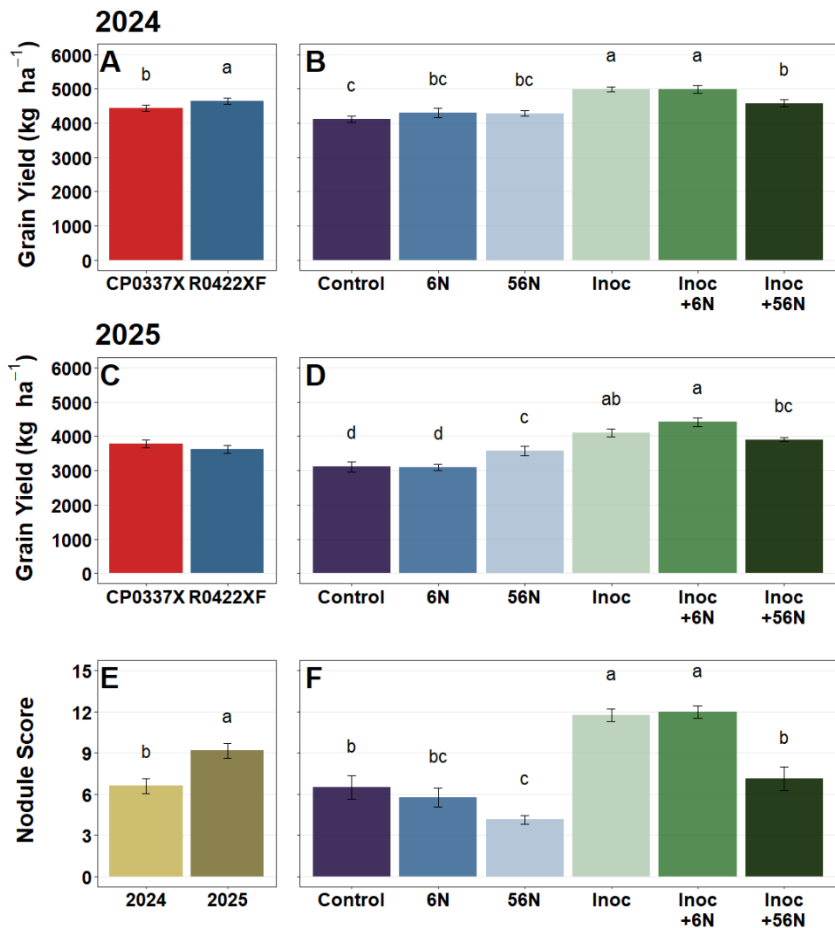


Figure 1. Effect of genotype (A and C) and treatment (B and D) on soybean seed yield in 2024 and 2025 and effect of year (E) and treatment (F) on soybean nodule score. Treatments include none (Control), 6 kg N ha⁻¹ (6N), 56 kg N ha⁻¹ (56N), rhizobium inoculation (Inoc), rhizobium inoculation with 6 kg N ha⁻¹ (Inoc + 6N) and rhizobium inoculation with 56 kg N ha⁻¹ (Inoc + 56N). Error bars are standard errors of the means and bars labelled with the same letter within a panel are not statistically different at $P \leq 0.05$.

Dry bean seed yield was significantly affected by year and treatment as well as year by genotype and year by treatment interactions (Table 1). Viper produced higher seed yields than Cowboy in 2024 but not 2025 (Fig. 2A and 2C). Treatment effects were observed only in 2024 with the 6N treatment producing the highest yields (Fig. 2B). Dry bean biomass was significantly affected by year but not genotype or treatment (Table 1) with more biomass in 2025 (4990 kg ha⁻¹) than 2024 (3864 kg ha⁻¹).

Significant genotype interactions with year and treatment were identified for dry bean nodule scores (Table 1). Therefore, the two beans were analyzed separately. No year effect was observed for Cowboy (Fig. 2E). However, nodule scores were higher in 2025 than 2024 for Viper (Fig. 2G). Treatment effects on nodule scores were significant. The Inoc treatment produced the highest nodulation score for Cowboy (Fig. 2F) and the lowest for Viper (Fig. 2H). The Control treatment produced the highest nodulation score for Viper (Fig. 2H) and the second highest score for Cowboy (Fig. 2F). The addition of

56 kg N ha⁻¹ in the 56N and Inoc + 56N treatments resulted in a significant decrease in nodulation scores relative to the control treatment for both beans.

Table 2. Mean separation of soybean biomass, seed protein and seed oil as affected by year (seed oil only), genotype and treatment in 2024 and 2025.

	Biomass	Biomass	Seed Protein	Seed Protein	Seed Oil
	kg ha ⁻¹	kg ha ⁻¹	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹
	2024	2025	2024	2025	
Year					
2024	-	-	-	-	196.9 b
2025	-	-	-	-	199.6 a
Variety					
CP0337X	3834	5372	291.3 b	267.5 b	197.4 b
R0422XF	3768	5088	311.1 a	278.8 a	199.1 a
Treatment					
Control	3745 ab	4257 b	280.8 c	261.4 c	204.1 a
6N	3783 ab	4766 b	290.1 c	258.1 c	202.8 ab
56N	3414 ab	6065 a	292.1 c	262.3 c	201.2 b
Inoc	4297 a	4837 b	321.3 a	289.8 a	192.4 d
Inoc + 6N	4228 ab	4984 b	316.9 ab	293.4 a	192.7 d
Inoc + 56N	3350 b	6473 a	306.1 b	273.9 b	196.3 c

Mean values within a column that share the same letter are not significantly different at $P \leq 0.05$.

DISCUSSION

In this study, both genotypic selection and agronomic practices influenced soybean seed yield and quality. Genotype effects on seed yield varied by growing season but the pattern of effects on seed protein was consistent between years indicating that genotype by environment interactions impact seed yield more than seed protein. The lower N fertilization rate of 6 kg ha⁻¹ failed to generate a yield response and the addition of N at 56 kg ha⁻¹, even when combined with inoculation, suppressed the yield gains observed by inoculation alone and reduced the effectiveness of inoculation. This is evident in the reduction of nodulation scores in the Inoc + 56N treatments relative to the other inoculated treatments (Fig. 1 E and F). These results indicate that successful rhizobium inoculation is more critical than N fertilization to achieve maximum soybean seed yield and seed protein in fields with no recent history of soybean as utilized in this study. In addition, N fertilization of soybean at rates less than required to attain full yield potential may have negative impacts on yield.

The impact of rhizobium inoculation on dry bean was very different from that observed for soybean. Inoculation of both dry beans resulted in no improvement in seed yield or nodulation scores (Fig. 2 E,F,G and H). Poor nodulation was observed in Control treatments for soybean, whereas dry bean nodulation patterns were similar between the Control and Inoc treatments. This suggests that indigenous soil rhizobium

populations exist, even in the absence of a field history of dry bean, that compete with the inoculant strain for nodule occupancy or are capable of nodulation and N fixation at levels that are indistinguishable from the inoculant strain.

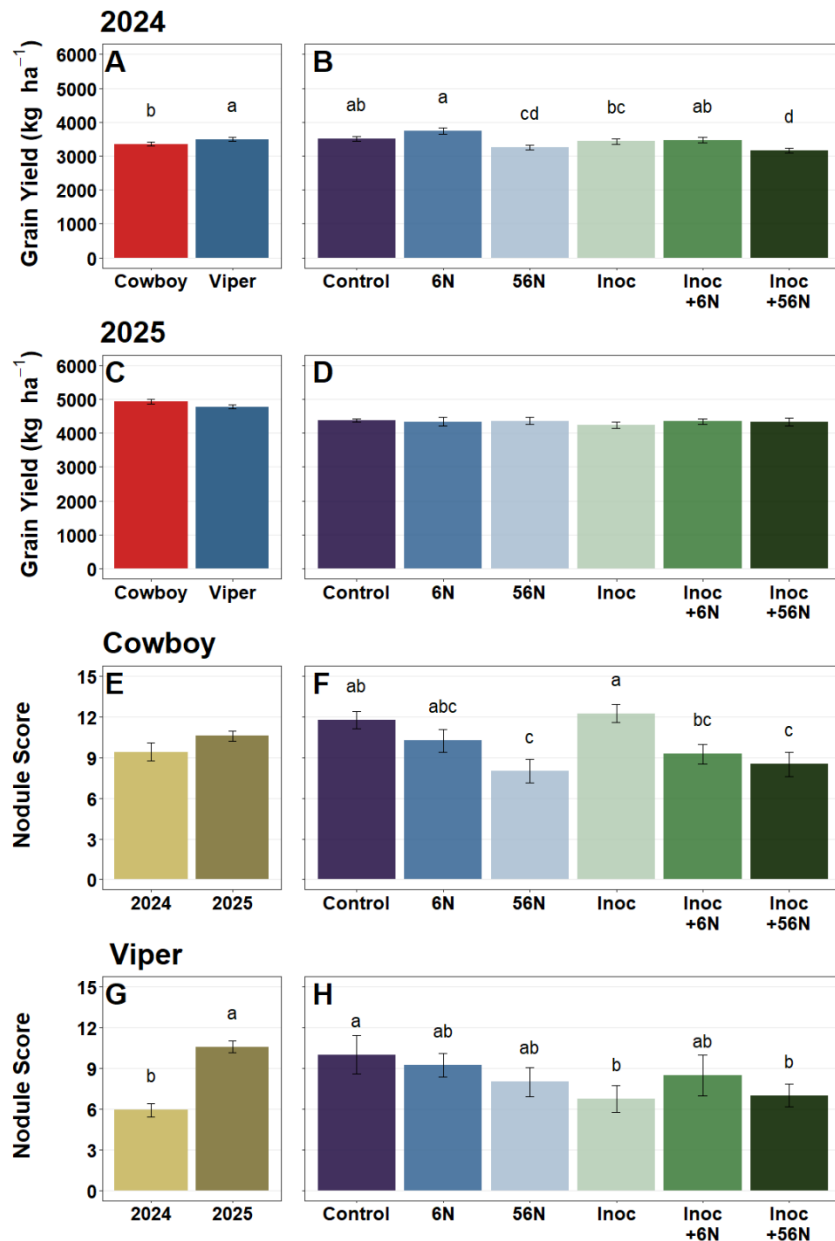


Figure 2. Effect of genotype (A and C) and treatment (B and D) on dry bean seed yield in 2024 and 2025 and effect of year (E and G) and treatment (F and H) on Cowboy and Viper nodule scores. Treatments include none (Control), 6 kg N ha⁻¹ (6N), 56 kg N ha⁻¹ (56N), rhizobium inoculation (Inoc), rhizobium inoculation with 6 kg N ha⁻¹ (Inoc + 6N) and rhizobium inoculation with 56 kg N ha⁻¹ (Inoc + 56N). Error bars are standard errors of the means and bars labelled with the same letter within a panel are not statistically different at $P \leq 0.05$.

Either of which would explain the lack of response to the commercial inoculant. Furthermore, the negative impacts of N fertilization on seed yield and nodulation scores observed with soybean were less pronounced for dry bean with reduction in nodulation scores being much smaller to absent and a small yield reduction observed in only one of the two study years.

The results of this study indicate that inoculation of soybeans in Eastern Montana fields with little or no history of the crop is critical to maximize yield, and the yield benefits are more than adequate to generate a net positive return on the input. On the other hand, rhizobium inoculation of dry beans appears to offer little benefit even in the

absence of a dry bean field history. Finally, N fertilization of both soybean and dry bean at levels below that required for full N fertility should be undertaken with caution as the negative impacts on nodulation can outweigh the benefits of partial N supplementation.

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PLANT TISSUE ANALYSIS: DO THE NUMBERS MAKE SENSE?

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ABSTRACT

Corn plant tissue analysis results from 2016 to 2025, inclusive, were compiled for survey purposes. The survey results for two growth stage ranges (VE-V4 and R1) were compared to published sufficiency ranges. In several cases, these sufficiency ranges may have overestimated the number of deficient plants, including nitrogen, phosphorus, magnesium, zinc, and sulfur. Refinement of the ranges for corn grown in the High Plains region is probably warranted.

INTRODUCTION

Plant analysis is a useful tool for diagnosing nutrient deficiencies and improving nutrient management. Crop advisers, retailers, and crop consultants often collect plant samples for lab analysis as a service to their corn producing clients. Analytical results are meaningless unless interpretations are available to help make management decisions.

Common interpretations include sufficiency ranges and survey values. Sufficiency ranges have been established by research to identify concentration ranges for essential nutrients within which optimum growth and/or yield can occur. These ranges are specific to certain plant parts and plant growth stages. Survey values are general concentrations or ranges based on acceptable visual appearance or acceptable yield.

Inquiries to several Extension specialists indicated that interpretations for corn plant tissue analysis were generally based on those published in Southern Cooperative Series Bull. #394, "Plant Analysis Handbook II", or "Plant Analysis Handbook III". The background references for the sufficiency levels often date from the 1970's to the 1990's. Corn yields have improved substantially since then, so the question arises whether the sufficiency levels accurately represent current conditions. The intent of this presentation is simply to compare commonly used sufficiency ranges to a survey of recent plant analysis results. It should be noted that the concentrations in the survey are not correlated to final yield.

MATERIALS AND METHODS

The results of corn plant tissue samples submitted to ServiTech Laboratories from 2016 to 2025, inclusive, were compiled for this survey. Results were grouped into six growth stage ranges: VE-V4, V6-V10, V12-V18, VT, R1, R2-R3. This represents early, mid-, and late vegetative or reproductive growth stages. The data set for each nutrient was initially trimmed by deleting the highest and lowest 0.25% of the population to eliminate extreme outliers. Table 1 lists the final size of the data populations. Data for each nutrient and growth stage range is shown graphically in Figures 1(a) through 1(n)

using box-and-whisker plots. The whisker ends represent the 1st and 99th percentiles. The box ends represent the 25th and 75th percentiles. The box center represents the 50th percentile (median). The larger boxes with dashed outlines represent the sufficiency ranges published in SCSB #394 for “Seedling (< 4 inches in height)” and “Tasseling/Bloom”. This presentation style allows visual comparison of the sufficiency ranges to the survey population.

RESULTS AND DISCUSSION

The sufficiency ranges for the VE-V4 stage suggest that potentially 32% of the samples are N deficient, 35% are P deficient, and 3% are S deficient. Results suggest that potentially 7%, 3%, and 20% of samples for each of the cations, K, Ca, and Mg, are deficient. About 1% to 3% of Zn, Cu, and B results would be considered deficient.

The SCSB ranges note that the optimum N:S ratio should be between 10 and 15 at all growth stages, but sulfur is limiting at ratios greater than or equal to 18. The survey results show the N:S ratio for 43% of the VE-V4 samples were between 15 and 18. About 16% of samples had an N:S ratio greater than 18. This would suggest that 59% of the samples are potentially sulfur deficient according to the SCSB ranges.

The silking (R1) stage is generally considered to be the optimum time to evaluate fertility status with plant analysis. The sufficiency ranges at R1 suggest that potentially 42% of the samples represented in the survey data are N deficient, 26% are Mg deficient, and 27% are Zn deficient. About 11% and 2% of the K and Ca results, respectively, were below the sufficiency ranges. 2% and 4% of the Cu and B results, respectively, were below the sufficiency levels. About 60% of the N:S results at R1 are between 15 and 18 and 12% exceed N:S 18. This would suggest that according to the sufficiency range, a potential total of 72% of samples might be considered deficient.

CONCLUSIONS

Applying the SCSB #394 sufficiency ranges to the survey results suggested potential large-scale deficiencies for certain nutrients, notably N, S, Zn, and Mg. These ranges or very similar ranges are used for diagnostic and monitoring purposes by Extension, crop advisers, and consultants. The sufficiency levels are based on historical research in many cases. It may be prudent to review and revise them to reflect current corn genetics and production practices used in the High Plains region.

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Growth stage range		NPK	Secondary & micronutrients
VE – V4	Emerg. to 4-leaf	4,870	3,674
V6 – V10	6-leaf to 10-leaf	13,372	13,069
V12 – V18	12-leaf to 18-leaf	4,412	4,086
VT	Tasseling	4,419	2,855
R1	Silking	4,978	4,525
R2 – R3	Blister - Milk	4,193	3,970

	VE-V4	R1	VE-V4	R1
N %	4.00-5.00	2.80-4.00	Zn ppm	20-60 20-70
P %	0.40-0.60	0.25-0.50	Fe ppm	40-250 30-250
K %	3.00-4.00	1.80-3.00	Mn ppm	25-160 15-150
Ca %	0.30-0.80	0.25-0.80	Cu ppm	6-20 5-25
Mg %	0.20-0.60	0.15-0.60	B ppm	5-25 5-25
S %	0.18-0.50	0.15-0.60	N:S ratio	10-15 10-15

Figure 1. Distribution of corn plant tissue analysis results for (a) nitrogen and (b) phosphorus. Squares with dashed borders represent SCSB #394 sufficiency ranges.

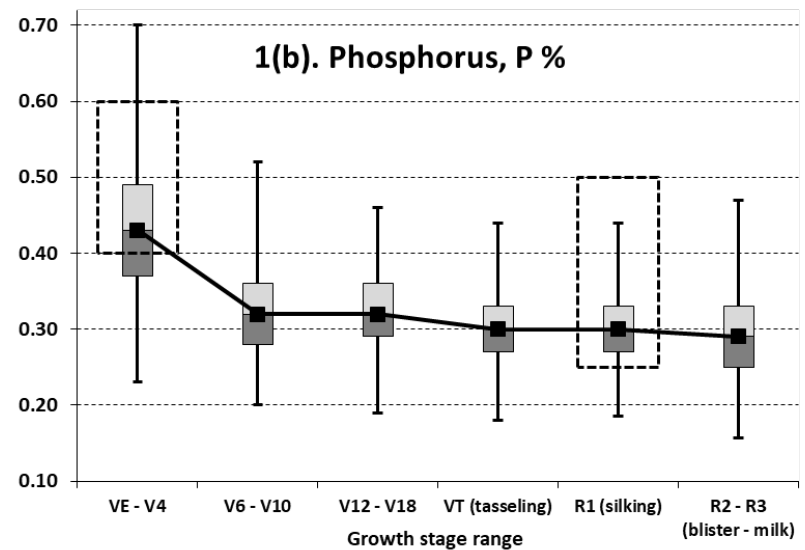
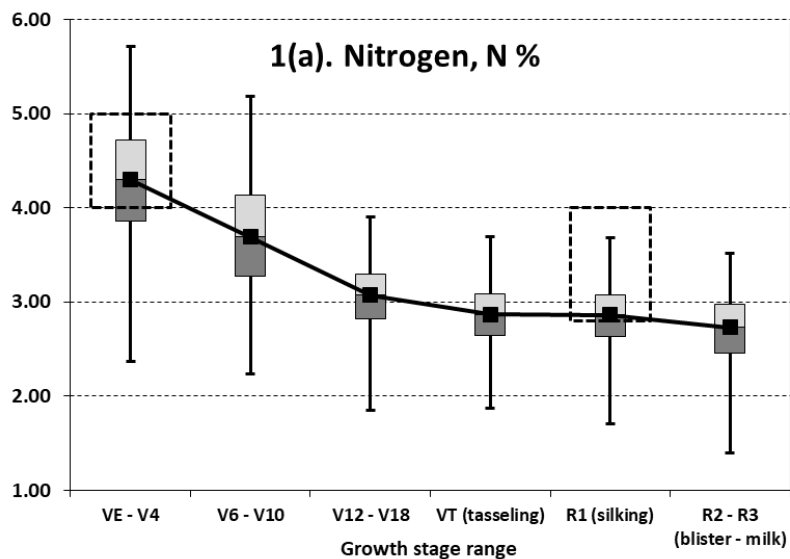


Figure 1. Distribution of corn plant tissue analysis results for (c) potassium, (d) calcium, (e) magnesium, and (f) sulfur. Squares with dashed borders represent SCSB #394 sufficiency ranges.

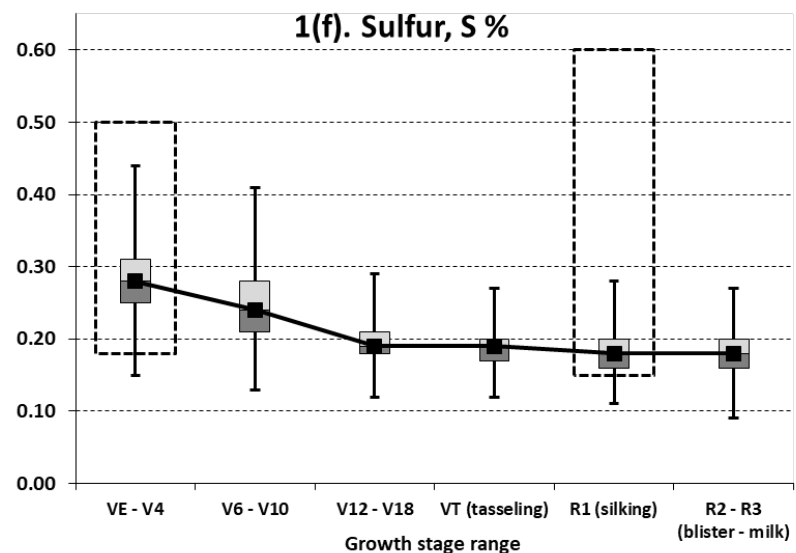
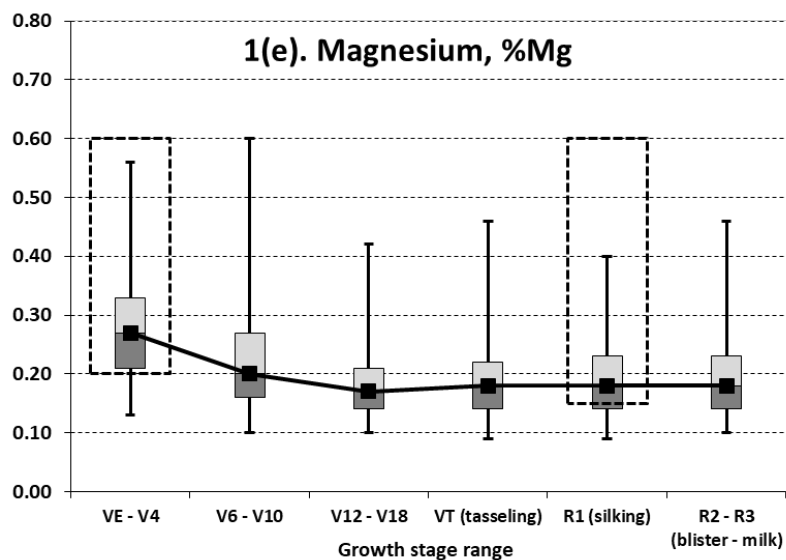
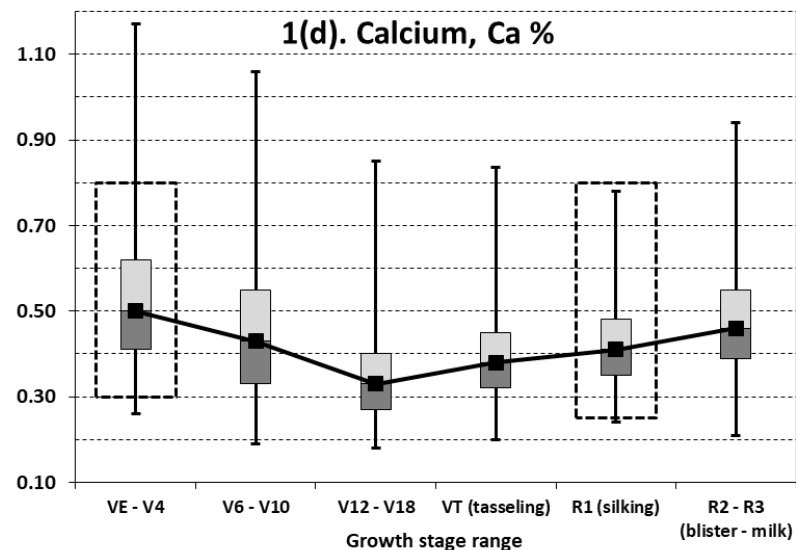
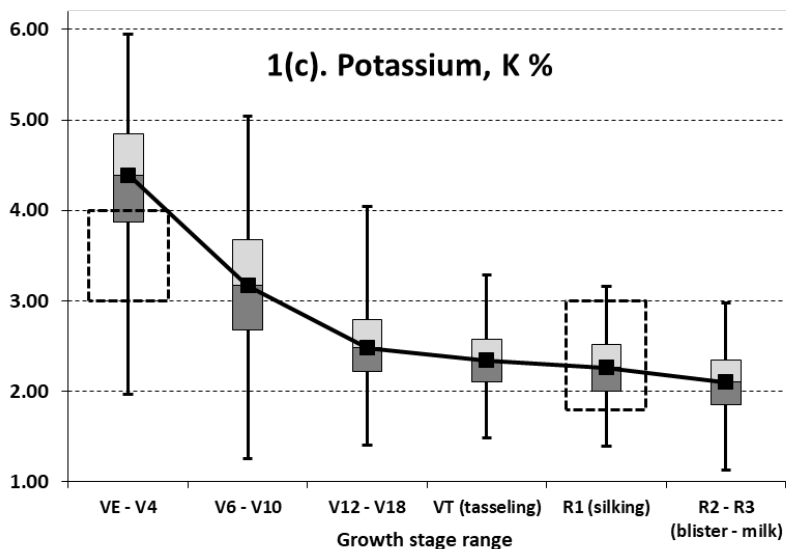


Figure 1. Distribution of corn plant tissue analysis results for (g) zinc, (h) iron, (i) copper, and (j) manganese. Squares with dashed borders represent SCSB #394 sufficiency ranges.

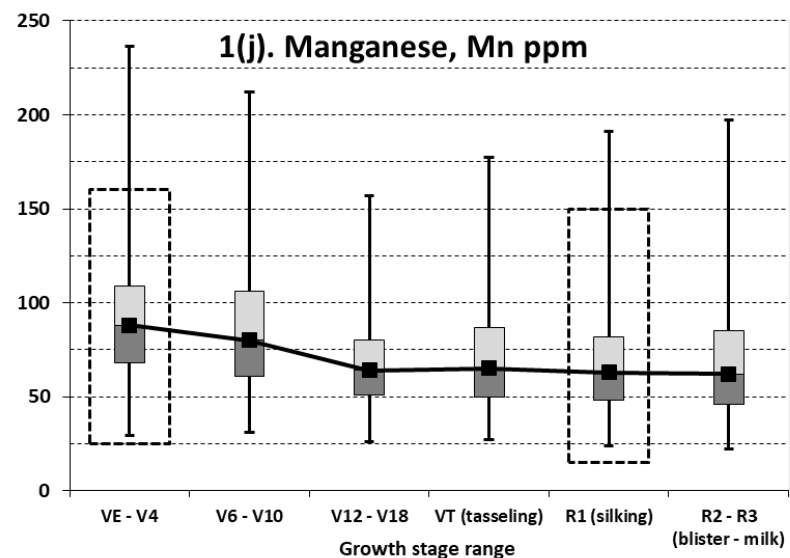
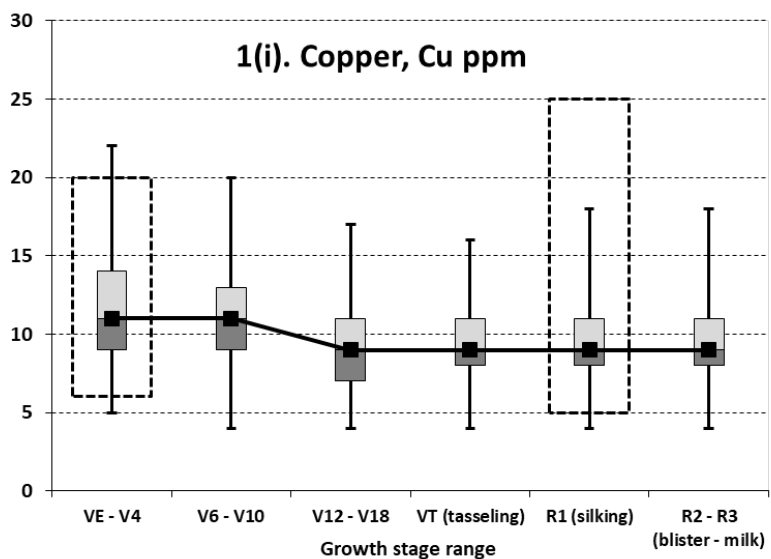
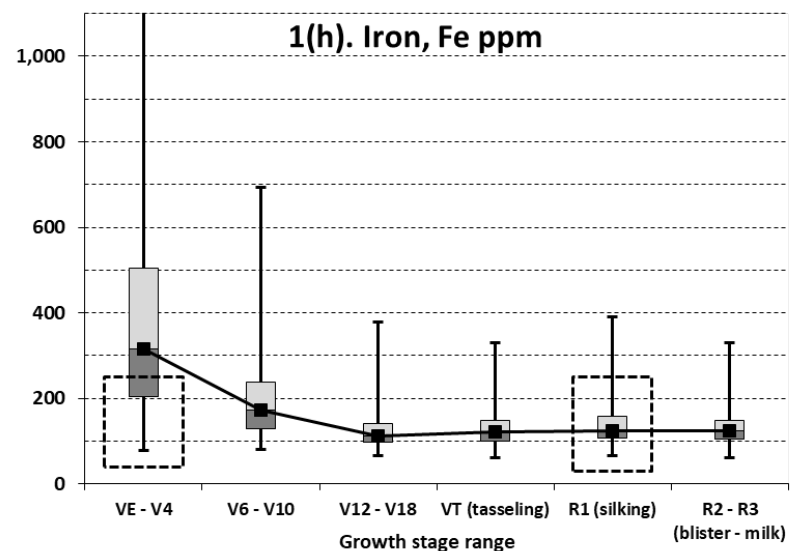
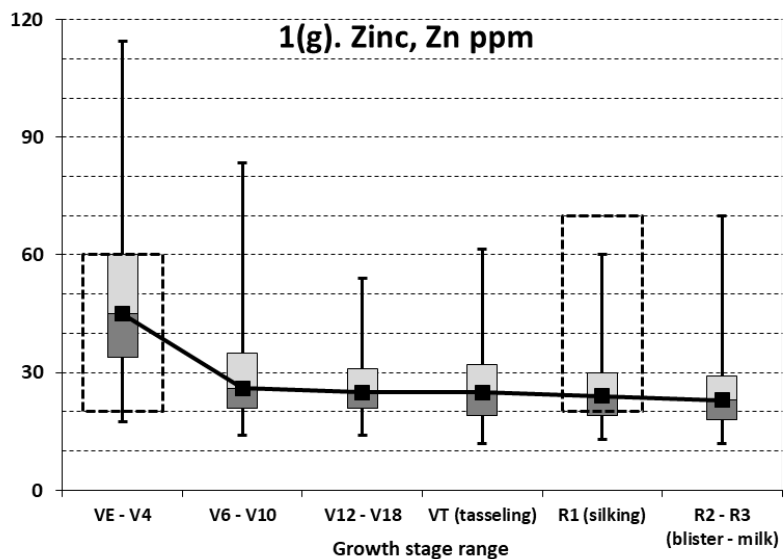
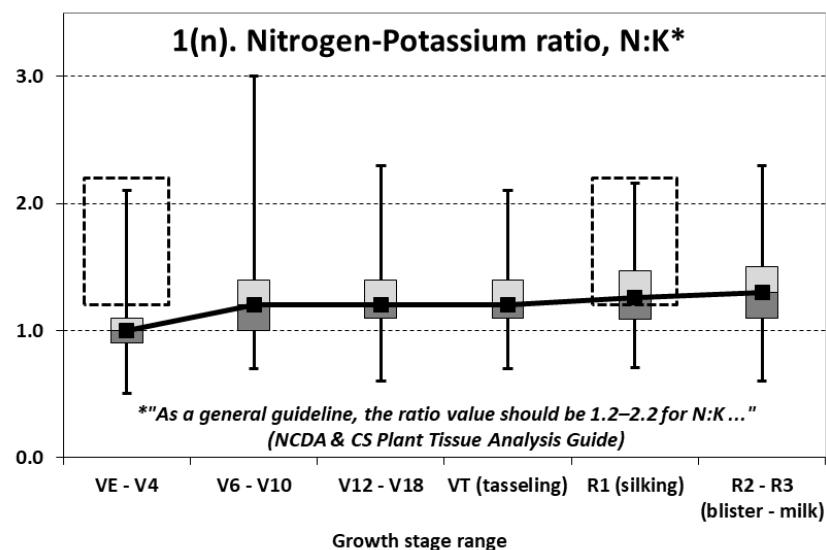
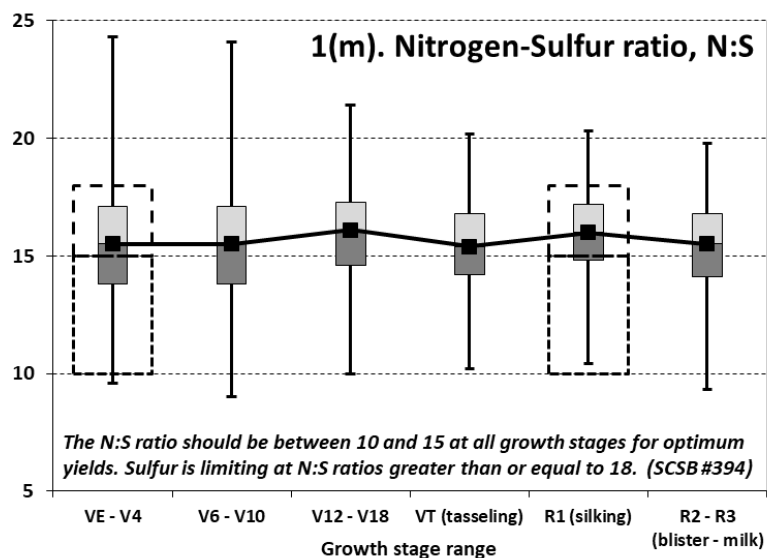
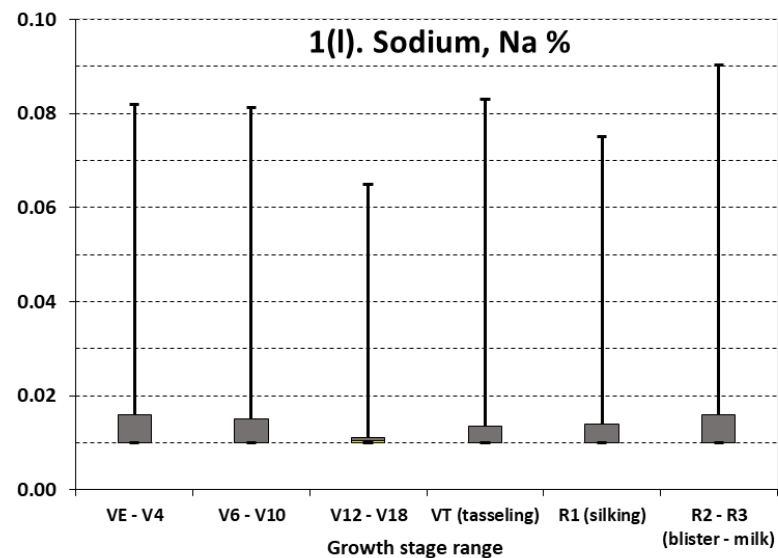
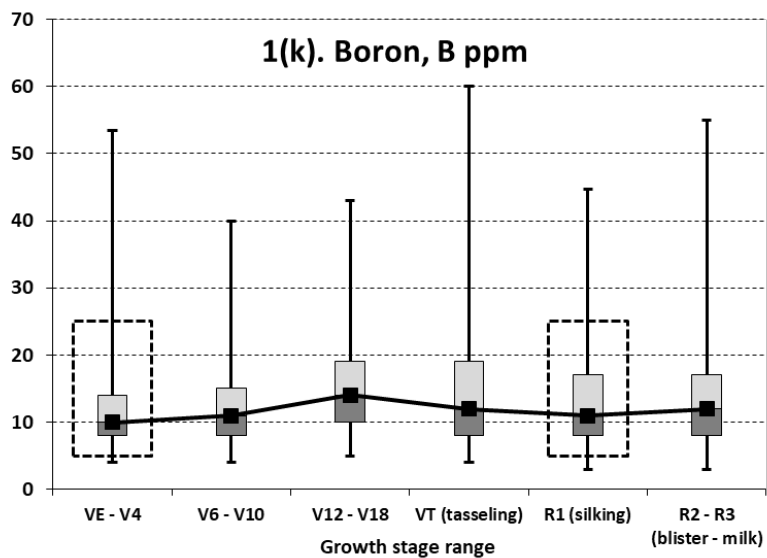


Figure 1. Distribution of corn plant tissue analysis results for (k) boron, (l) sodium, (m) nitrogen-to-sulfur ratio, and (n) nitrogen-to-potassium ratio. Squares with dashed borders represent SCSB #394 sufficiency ranges.



PHOSPHORUS AND POTASSIUM IMPACTS ON FIELD CROP PRODUCTION IN THE INTERMOUNTAIN WEST

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ABSTRACT

Macronutrients such as phosphorus (P) and potassium (K) are essential nutrients for plants, with fertilizers often supplementing soil nutrients to increase crop productivity. Fertilizer recommendations can vary significantly depending on the source and affect farm profitability considerably. Guidelines in Utah and many other states in the Intermountain West were developed decades ago and need to be evaluated. Current Utah State University (USU) recommendations identify 15 and 150 ppm (Olsen) as critical soil test values for P and K, respectively. As a part of national efforts to improve regional and state-level soil fertility guidelines, on-farm trials in 2021-2025 across Utah evaluated current USU Fertilizer Guidelines for P and K in common crops to the region.

Trial nutrient, duration, treatment rates, and crops grown varied across six sites for eleven and five total site-years of P and K trials, respectively. Fertilizer treatments were evaluated in alfalfa (*Medicago sativa*), corn (*Zea mays*), and winter wheat (*Triticum aestivum*) using crop yield, nutritive value, and economic returns. At repeating sites (sites 3-5), soil samples were collected by plot prior to fertilizer application each spring to assess soil nutrient changes. At site 6, P fertilizer source and timing were evaluated in addition to application rate. Preliminary results indicate that crop yield and quality were not impacted by K applications regardless of fertilizer rate or initial soil test value. Fertilizer P increased alfalfa yield with rates ≥ 50 lb P_2O_5 / acre across three years, but forage nutritive value was not affected. Wheat yield increased with rates ≥ 30 lb P_2O_5 /acre at site 6, with the fall applications yielding higher than the spring and P fertilizer source having no impact. These results indicate that USU fertilizer guidelines should possibly be reduced and that recommendations should be tested >1-2 years to evaluate potential yield and profit losses from under-fertilization.

INTRODUCTION

Phosphorus (P) and potassium (K) are two of the most common nutrients applied in crop production and have greatly contributed to crop yield improvements over the last 60 years (Weibe & Gollehon, 2006). Excessive applications of these nutrients can pose economic and environmental harm, with contamination of surface and ground water from excess P a growing concern (Carpenter, 2005). Soil tests assess nutrient status in the soil and direct fertilizer applications (Dahnke & Olson, 1990). Fertilizer recommendations can vary significantly depending on the source and impact crop

profitability considerably (Baker et al., 2026; Zhang et al., 2021). Guidelines in Utah and many other states in the region were developed decades ago and need to be evaluated and potentially updated (Lyons et al., 2023; Spargo et al., 2022). Current Utah State University (USU) recommendations identify 15 and 150 ppm (Olsen) as critical soil test values for P and K, respectively. As a part of national efforts to improve regional and state-level soil fertility guidelines, this work aims to 1) evaluate current USU fertilizer recommendations in common field crops, 2) compare impacts of P fertilizer source and application timing on wheat production, and 3) assess economic returns on fertilizer applications.

MATERIALS AND METHODS

Field research for these experiments was conducted in six fields on farms across the state of Utah in 2021-2025 to evaluate crop response to phosphorus (P) and potassium (K) fertilizer applications. Trial duration and crops grown varied among sites, with treatments compared in alfalfa (*Medicago sativa*), corn (*Zea mays*), and winter wheat (*Triticum aestivum*; Table 1). A composite soil sample comprising of 25-30 cores (12 × 0.75 in i.d.) collected in the spring at each site prior to trial establishment was analyzed to assess baseline soil fertility. Samples were air-dried for 6 to 10 days, ground to 0.08 in (2 mm), and mixed to ensure uniformity prior to analysis at the Utah State University (USU) Analytical Laboratory. The Olsen bicarbonate extract measured soil P and K, with ascorbic acid/molybdate blue colorimetric and atomic adsorption used to analyze P and K, respectively. To prevent nutrient deficiencies and isolate treatment impacts, USU fertilizer guidelines directed fertility needs for nutrients besides the trial nutrient at each site (Cardon et al., 2008).

Table 1. Crop and soil characteristics for each site.

Site #	Trial Nutrient	Trial Years	Crop	Soil pH	Organic Matter (%)	Soil P (ppm)	Soil K (ppm)
1	P and K	2021	Corn	7.8	2.1	7	374
2	P and K	2021	Corn	8.0	3.7	10	130
3	P and K	2023-2025	Alfalfa	7.9	1.4	9	71
4	P	2023-2024	Corn-Wheat	7.8	1.9	13	199
5	P	2023-2025	Corn-Wheat-Corn	7.7	2.6	6	277
6	P	2025	Wheat	7.8	1.2	13	69

Fertilizer treatment rates varied among sites (Table 2), with all treatments hand-broadcast in the spring of each year at sites 1-5 as dry, granular products. Triple superphosphate (TSP; 0-45-0) and muriate of potash (0-0-60) supplied P and K, respectively, for fertilizer treatments. At site 6, P fertilizer source and application timing were compared in addition to application rate. At this site, monoammonium phosphate (MAP; 11-52-0) and TSP treatments were each applied at rates of 0, 30, 60, 90, and

120 lb P₂O₅/acre in both in the fall and spring, with applied nitrogen (N) from MAP treatments balanced across all plots using ammonium nitrate (34-0-0) in the spring of 2025. Plot dimensions were 15 × 30 ft at sites 1-5 and 10 × 40 ft at site 6, with plots six rows wide at corn sites (sites 1, 2, 4, and 5). Crop yield was measured at each site using standard hand-harvest methods or research-scale machinery. Forage subsamples were dried and ground after harvest to calculate treatment yields. All samples were analyzed using near-infrared spectroscopy (NIRS) to assess nutritive value using their respective crop equations. The legume hay equation measured or calculated crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), total digestible nutrients (TDN), relative feed value (RFV), and relative forage quality (RFQ) of alfalfa samples. The unfermented corn silage equation determined CP, ADF, NDF, TDN, and starch content for silage corn samples. Whole-grain wheat samples were evaluated using CP, starch, gluten, and Zeleny values produced by the wheat equation. At sites where trials were repeated (sites 3-5), composite soil samples collected by plot (6-8 cores) prior to fertilization each year evaluated fertilizer impacts on soil nutrient levels. Economic returns on fertilizer applications were determined using fertilizer costs from local fertilizer dealers and crop prices from regional reports and United States Department of Agriculture National Agricultural Statistics Service (USDA-NASS, 2023).

Crop and soil data were analyzed by site using the MIXED procedure of SAS (SAS Version 9.4 SAS Institute Inc.). The (Pairwise Difference) PDIFF procedure of SAS was used for mean separations using Fisher’s protected LSD at $\alpha = 0.05$.

Table 2. Treatment fertilizer application rates at sites 1-5.

Site #	P Rates (lb P ₂ O ₅ /acre)	K Rates (lb K ₂ O/acre)	Control
1	50, 100, 150, 200	60, 120, 180, 240	0P/0K
2	50, 100, 150, 200	60, 120, 180, 240	0P/0K
3	0, 50, 100, 150, 200, 250	0, 60, 120, 180, 240	0P/0K, 0P, and 0K
4	0, 50, 100, 150, 200, 250	-	0P
5	0, 50, 100, 150, 200, 250	-	0P

RESULTS AND DISCUSSION

Silage Corn

Phosphorus and potassium applications rarely impacted silage corn yield or nutritive value. At sites 1 and 2, all fertilizer treatments were similar to the 0P/0K control in 2021. At site 5, overall yields were higher in 2025 than 2023, but P treatments did not differ from the 0P control in either year. At site 4, P application did not increase yield, but the 200 and 250-lb P rates had lower nutritive value than the control and 150-lb treatments. The higher P treatments averaged 25.8, 46.1, and 69.9% for ADF, NDF,

and TDN, respectively, while the control and 150-lb treatments averaged 22.2, 41.2, and 72.2% for these quality parameters, respectively.

Alfalfa

At site 3, the year × treatment interaction was significant for yield, as were the main effects of year and treatment. The 0P/0K control and 0P control treatments yielded similarly and were consistently the lowest every year (Figure 1). All K treatments received 150 lb P₂O₅/acre and all P treatments received 120 lb K₂O/acre to ensure that these nutrients would not be limiting. Potassium applications had no impact on alfalfa yield, with all K treatments yielding similarly to the 0K control. The 0K control yielding higher than the 0P/0K control and 0P control treatments indicates that P applications of any rate increased alfalfa yield while K applications did not.

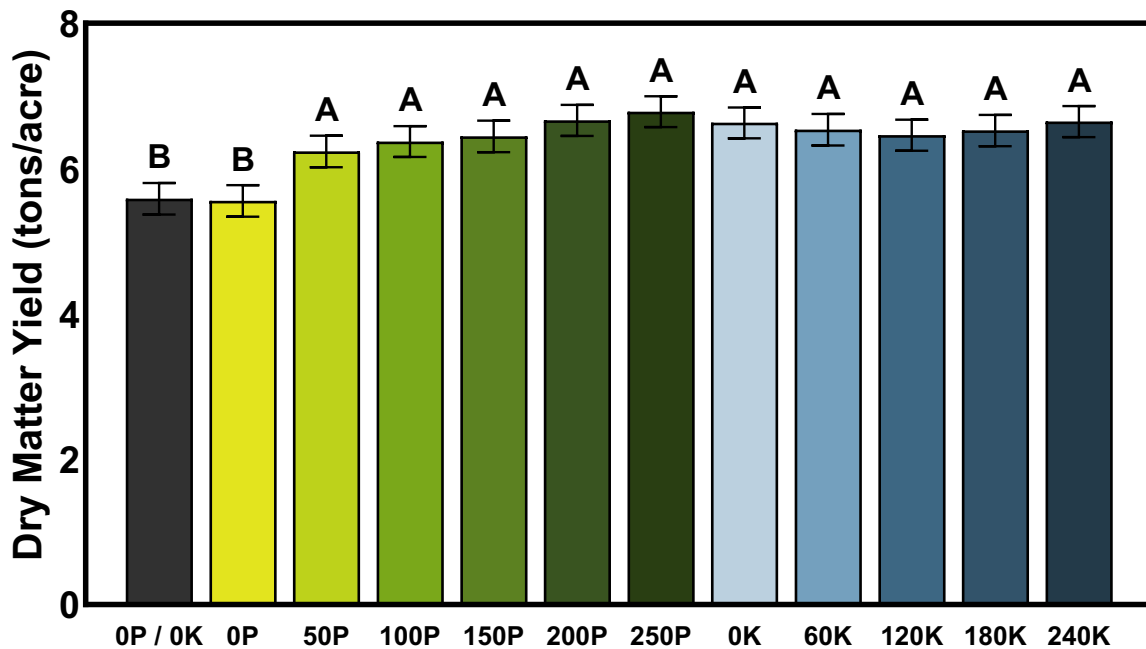


Figure 1. Alfalfa dry matter yield across years (2023-2025) at site 3. Letters above bars represent means separations conducted by treatment using $\alpha = 0.05$.

Phosphorus and K treatments were analyzed separately and without the 0P/0K control to isolate nutrient impacts. All P rates increased yield compared to the 0P control, but the 250-lb rate was significantly higher than the 50-lb rate. Alfalfa yield was not affected by K application, with all rates yielding similarly to the 0K control. Fertilizer applications did not impact forage nutritive or market value, with all alfalfa classified as ‘Supreme’ forage using USDA Hay Quality Designation Guidelines (USDA-Agricultural Marketing Service [USDA-AMS], 2003).

Wheat

Phosphorus applications did not impact wheat yield at sites 4 or 5 in 2024. At site 4, grain gluten content was higher for the control than the 50, 100, and 150-lb treatments, but no other differences in nutritive value were observed at either site.

At site 6, the timing × rate interaction was significant for yield, as were the main effects of timing and rate. All fall-applied P applications increased yield by 10-20 bu/acre, but the spring application treatments did not differ from one another (Figure 2A). Fall P treatments yielded higher than spring treatments, yielding 136.7 and 130.1 bu/acre, respectively. When P rate was evaluated across both timings and sources, all P rates yielded higher than the control, and the 60 and 120-lb rates higher than the 30-lb rate (Figure 2B). Fertilizer source and its interactions were not significant, indicating that TSP and MAP fertilizers performed similarly. Phosphorus applications had no impact on wheat nutritive value.

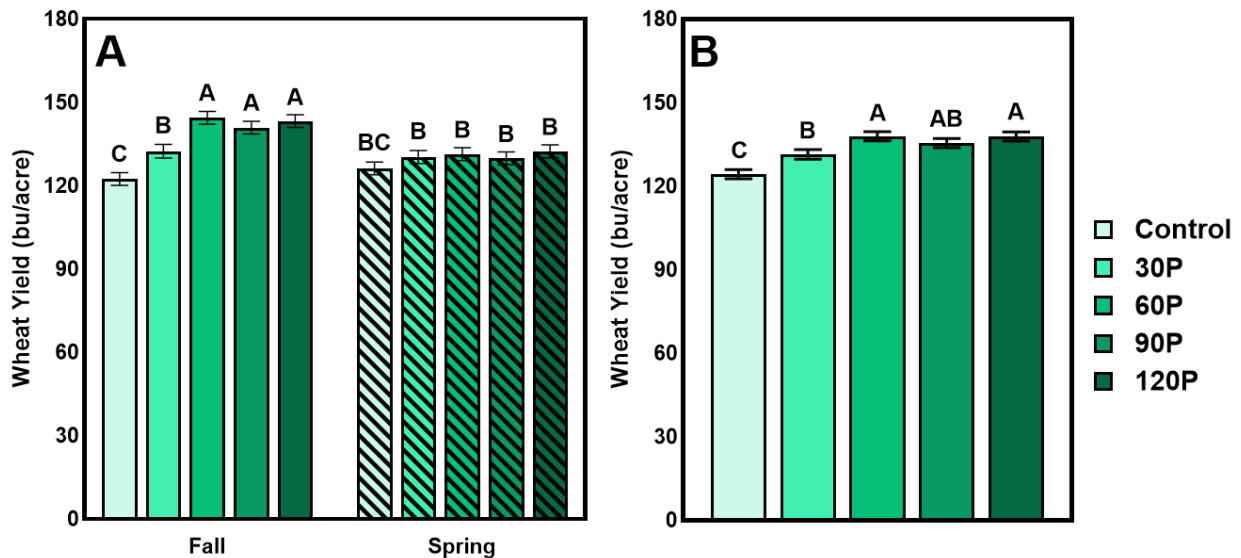


Figure 2. (A) Wheat yield at site 6 by application timing where the timing × rate interaction was significant with spring applications denoted by striped bars. (B) Wheat yield by P application rate across timings and fertilizer sources. Letters above bars represent means separations conducted by treatment using $\alpha = 0.05$.

CONCLUSIONS

Potassium applications had no impact on crop productivity at any site regardless of crop grown, K rate applied, or initial soil test levels. Phosphorus applications increased alfalfa yield at site 3 with rates ≥ 50 lb P_2O_5 /acre but did not affect forage nutritive value. Wheat yields at site 6 increased with P rates ≥ 30 lb P_2O_5 /acre, with fall applications yielding higher than spring applications and P source having no effect. Silage corn yield was not affected by P or K applications, but forage nutritive value differences were observed at one site. The low frequency of crop impacts and economic returns of P and K fertilization in low-testing soils in this study indicates that USU

fertilizer guidelines should possibly be reduced and that recommendations tested >1-2 years to evaluate potential yield and profit losses from under-fertilization.

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WHEAT ZINC NUTRITION: AGRONOMIC BIOFORTIFICATION THAT DELIVERS YIELD AND BETTER GRAIN NUTRITION

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ABSTRACT

Low Zn availability in calcareous soils is a common issue in the Canadian prairies, where much of the wheat is exported, making Canada one of the world's largest wheat exporters. Globally, 19% of the population, mostly pregnant women, infants, and children, suffers from Zn deficiency, highlighting the need to enhance Zn bioavailability in wheat grain. Agronomic biofortification offers a promising strategy to improve grain nutrient density while optimizing plant health and development. While many studies have examined Zn fertilization, either alone or with biostimulants, its effects on phytate concentration and Zn bioavailability in wheat grain remain underexplored. Previous research has shown that high soil or foliar-applied Zn rates can enhance grain Zn bioavailability, but economic and environmental concerns have limited widespread adoption. This underscores the need for alternative fertilization strategies that align with existing cropping systems and sustainability goals.

This study tested practical agronomic biofortification to raise grain zinc and its bioavailability and evaluated yield impacts in Canadian context. Over two years at four site-years on calcareous clay and sandy loam in southern Manitoba, we compared phosphorus and zinc sources (MAP, MAP + granular zinc sulfate, co-granulated phosphorus-sulfur-zinc; MicroEssentials® SZ®) and placements (broadcast-incorporation, side-band, seed-row) with or without foliar zinc, potassium, and biostimulants applied at 2-leaf and anthesis stages. Grain and straw nutrients were quantified after acid digestion, and zinc bioavailability was indexed by the phytic acid to zinc molar ratio.

Across site-years, zinc fertilization increased wheat yield by 8.3% (3.8 bu/ac) compared with the Zn unfertilized control, with banding at seeding out-yielding broadcast-incorporation. The largest and most consistent gains in grain zinc concentration were achieved when the co-granulated product was placed in the seed-row and supplemented with foliar zinc, raising grain zinc by ~27–60% at the two most responsive site-years (to ~41–43 mg kg⁻¹). Adding potassium or the biostimulant mix produced small effects but were not significant. The phytic acid to zinc ratio ranged ~27–38 and improved by about 25% with foliar zinc application, while phosphorus fertilization did not systematically increase phytic acid. Integrating seed-row co-granulated with well-timed foliar zinc application is a practical strategy to improve grain zinc bioavailability in Canadian prairie wheat systems. However, stronger and more consistent gains may require higher foliar zinc rates.

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GENOTYPIC VARIATION IN WINTER WHEAT YIELD COMPONENTS RESPONSE TO NITROGEN MANAGEMENT AND SEEDING DENSITY

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ABSTRACT

Achieving optimal winter wheat grain yield requires understanding genotypic variations in yield component formation under nitrogen (N) application timing and seeding density management strategies. This study evaluated whether modern winter wheat genotypes exhibit differential yield formation pathways under varying N timing and seeding rate conditions, and whether reducing N rates while increasing seeding density (or vice versa) could maintain yields while reducing input costs. Additionally, we examined which yield components primarily drive productivity differences. Two winter wheat genotypes (Showdown and Butler's Gold) were examined under two N application timings (at tillering and at jointing), three seeding rates (700,000, 900,000, and 1,100,000 seeds ha⁻¹), and two N rates (60 and 120 kg N ha⁻¹) across two Oklahoma environments. Genotypes demonstrated contrasting yield formation strategies under different management scenarios. Under Tillering N application, Showdown achieved 3,790 kg ha⁻¹ compared to Butler's Gold's 3,134 kg ha⁻¹, representing a 21% yield advantage ($p < 0.01$). N application timing significantly affected yield response to seeding rate: the 700,000 and 900,000 seeding rates produced 3,694 and 3,615 kg ha⁻¹, respectively, compared to 3,077 kg ha⁻¹ for 1,100,000 seeds ha⁻¹ under Spring timing ($p < 0.05$), while Fall timing showed no significant seeding rate effects. Higher N rate (120 kg ha⁻¹) increased grain protein content but did not significantly improve yield over 60 kg ha⁻¹, suggesting opportunities for N rate optimization.

Showdown consistently maintained superior spike density (106.8 vs. 81.6 spikes m⁻²) and total grain number (2,585 vs. 1,688 grains m⁻²) compared to Butler's Gold at Tillering application ($p < 0.01$). The 700,000 seeds ha⁻¹ produced 24 grains spike⁻¹ compared to 21 grains spike⁻¹ for 1,100,000 seeds ha⁻¹ under Spring application ($p < 0.01$), highlighting the density productivity trade-off. Showdown's advantage in grains per spike was consistent across timings (25.0 vs. 20.5 at Tillering; 18.5 vs. 15.8 at Jointing, $p < 0.001$). Spike number showed no significant response to seeding rate, while grain weight remained relatively stable, identifying grains per spike as the critical compensatory mechanism. This study demonstrates that grains per spike emerges as the critical yield component driving genotypic differences, with Showdown's 22% advantage explaining its superior performance. The effect of N timing and seeding rate reveals that Tillering N application enables yield compensation at lower seeding densities, while N rate can be increased for protein targets rather than yield maximization. These findings establish a foundation for developing resource efficient management practices where reduced seeding rates (700,000-900,000 seeds ha⁻¹) combined with Tillering N application at 60 kg ha⁻¹ optimize input costs while maximizing yield potential in modern winter wheat production systems.

SHORT-TERM CHANGES IN SOIL PROPERTIES FOLLOWING SIMULATED WILDFIRE AFTER WINTER WHEAT HARVEST

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ABSTRACT

Wildfire risk is increasing across croplands in the semi-arid Great Plains where residue accumulation and drought conditions make production systems highly vulnerable to fire. Wildfires can rapidly remove residue cover, reduce soil organic carbon (SOC), and soil water content, impacting crop productivity. However, little is known about how cropland soils respond immediately after burning when post-fire management decisions must be made. This study evaluated short-term changes in soil properties following a simulated wildfire in a winter wheat-based cropping system in western Kansas. A control burn was conducted in 2025 to simulate wildfire conditions in a 16-acre field of winter wheat stubble at the Kansas State University Agricultural Research Center near Hays, KS. One week after burning, each block was divided into ten plots and assigned soil recovery treatments in a randomized complete block design. Soil samples were collected before and two weeks after burning to quantify immediate postfire baseline conditions prior to recovery treatments implementation. Cover crops were planted in September, and manure and other soil amendments were applied in October.

Preliminary results showed significant declines in SOC at both sampling depths (0-2 and 2-6 in), with the greatest losses near the surface soil. Soil penetration resistance increased at both depths, and bulk density increased at the 2-6 in depth, indicating subsurface compaction. Infiltration decreased by 62% (6.44 to 2.44 in hr^{-1}), and residue cover dropped from 90% in the unburned control to 45% in the burned field. These results demonstrate that burning rapidly degrades SOC and soil physical properties, reducing water infiltration and increasing compaction risk in semi-arid winter wheat-based systems. These findings highlight the vulnerability of cropland soils to wildfire and the need for post-fire management strategies, such as cover crops and organic soil amendments to restore soil function and resilience. Ongoing work will assess soil recovery one year after treatment implementation.

INTRODUCTION

Wildfires are becoming an increasingly important disturbance in semi-arid cropping systems, where drought, high temperatures, and the accumulation of post-harvest residues increase the risk of fire (Vermeire et al., 2005). In winter wheat-based cropping systems of the central Great Plains, surface residues play a critical role in moderating soil temperature, conserving moisture, and protecting soil structure under water-limited conditions (Rasmussen et al., 1986; Dao, 1993). When crop stubble

burns, this protective cover is rapidly removed, leaving the soil surface exposed and more susceptible to surface sealing and compaction, which can restrict water infiltration and root growth (Valzano et al., 1997).

Burning crop residue on the soil surface also alters soil carbon and nitrogen pools by eliminating organic inputs and reducing the incorporation of residue-derived carbon into the topsoil (Blanco-Canqui & Lal, 2009). As a result, declines in particulate organic matter and other labile carbon fractions have been widely reported, which are closely linked to aggregate stability and nutrient cycling (Six et al., 1999; Culman et al., 2012). These losses can trigger short-term changes in microbial activity and soil biochemical processes, particularly near the soil surface where heat exposure is greatest (Dormaar & Carefoot, 1996).

Soil biological indicators respond rapidly to disturbances that modify carbon availability and microhabitat conditions. In Great Plains cropping systems, enzyme activity and microbial community structure are strongly influenced by residue management and organic matter dynamics (Bandick & Dick, 1999; Acosta-Martínez et al., 2007). Following burning, shifts in microbial activity often occur in near-surface soils where both carbon loss and thermal stress are most severe (Dormaar & Carefoot, 1996).

Despite extensive research on residue management and soil health, relatively few studies have examined the immediate physical, chemical, and biological responses of cropland soils to wildfire (Valzano et al., 1997; Blanco-Canqui & Lal, 2009). Most of the research on wildfires have been conducted on rangelands or forest ecosystems with little work done on croplands. Agricultural soils differ from rangeland or forest ecosystems due to regular management, nutrient inputs, and crop residue management practices, all of which influence fire behavior and post-burn soil responses (Certini, 2005; Santín & Doerr, 2016). With increasing wildfire frequency in semi-arid cropping systems, there is a critical need to quantify immediate post-fire changes in soil properties to inform early management decisions.

This study evaluated short-term changes in soil properties following a simulated wildfire in a semi-arid winter wheat-sorghum-fallow system. By establishing post-burn baseline soil conditions, this work provides essential information for interpreting soil health responses and guiding post-wildfire management practices.

MATERIALS AND METHODS

This study was conducted at the Kansas State Agricultural Research Center near Hays, Kansas. The region is semi-arid, with an average annual rainfall of approximately 22.5 in and a mean annual temperature of 54.3°F (Kansas State University Mesonet, 2023).

A controlled burn of winter wheat stubble was conducted in summer 2025 to simulate wildfire conditions. Fire was ignited at a corner on the upwind side of each plot and allowed to burn as a headfire through the plot area, with a fully disked border providing a sufficient buffer for safe and continuous fire spread. One week after burning, each replicated block was divided into ten individual plots, and ten soil recovery treatments were assigned using a randomized complete block design with four

replications, each containing ten plots. Individual plots served as the experimental units for all soil measurements. Soil samples were collected prior to burning and two weeks after burning from individual plots within each block before implementation of recovery treatments, and were analyzed for soil properties.

Bulk density was determined from two intact soil cores collected at two depth intervals (0-2 in and 2-6 in), dried at 105°C and expressed on a dry weight basis. Soil water infiltration was measured using an MPD automated infiltrometer (Upstream Technologies Inc., Fridley, MN, USA), and infiltration rates were recorded in inches h⁻¹. Soil penetration resistance was measured using a penetrometer (FieldScout soil compaction tester (Spectrum Technologies Inc., Aurora, IL, USA) and recorded in megapascals (MPa).

Soil recovery treatments included Pervaide and C-20 Soil Builder, which were applied to the soil using a tractor-mounted sprayer at rates of 1 gal/acre and 454 lb/acre, respectively. Cattle manure application rate was 10 tons/acre, using a manure spreader. Cover crops consisting of a mixture of triticale (*× Triticosecale*; 15 lb/acre), hairy vetch (*Vicia villosa*; 15 lb/acre), cereal rye (*Secale cereale*; 20 lb/acre), and daikon radish (*Raphanus sativus*; 1.5 lb/acre) were planted following treatment application. All soil recovery treatments were fully implemented by November 20, 2025.

The experimental treatments included: (T1) Unburned, no-till control; (T2) Burned, untreated control; (T3) Pervaide; (T4) C-20 Soil Builder; (T5) Cattle manure (10 tons/acre); (T6) Cover crop; (T7) Manure + Cover crop; (T8) Pervaide + Cover crop; (T9) C-20 Soil builder + Cover crop; (T10) Manure + Disking. All statistical analyses were conducted using SAS version 9.4 (SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

Soil Carbon

Soil Carbon declined significantly from pre-burn to post-burn at both sampling depths, with the greatest losses near the surface at the 0-2 in depth (Fig. 1). This pattern is expected in semi-arid croplands because near-surface carbon is largely derived from crop residues that are readily combusted during fire events. Since soil carbon was measured two weeks after burning, immediate losses from residue combustion and heat-driven oxidation and thermal alteration of organic matter likely exceeded any short-term carbon inputs from ash. Low biomass inputs and exposed soil surfaces in semi-arid systems further increase the vulnerability of surface carbon to oxidation and redistribution. Similar short-term soil carbon declines following burning have been reported in other semi-arid agricultural and grassland systems (Abdalla et al., 2021; Fultz et al., 2016; Novara et al., 2013).

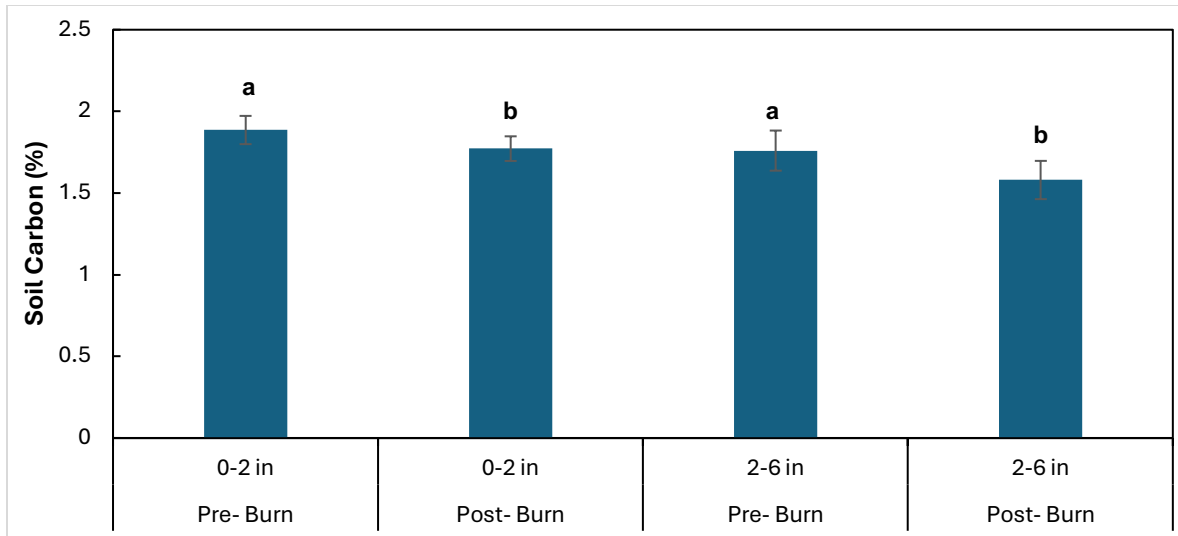


Fig.1. Short-term response of soil organic carbon to simulated wildfire in a semi-arid winter wheat-sorghum-fallow system in Hays, KS. Means with the same letter are not significantly different ($P < 0.10$).

Bulk Density

Bulk density did not differ between pre-burn and post-burn conditions at the 0–2 in depth (1.28 g cm^{-3} ; Fig. 2). However, bulk density increased significantly at the 2–6 in depth from 1.37 to 1.43 g cm^{-3} following burning. This subsurface increase indicates greater soil compaction after burning, likely resulting from residue loss and post-burn surface exposure, which increase susceptibility to compaction. These changes can restrict root growth and limit water movement through the soil.

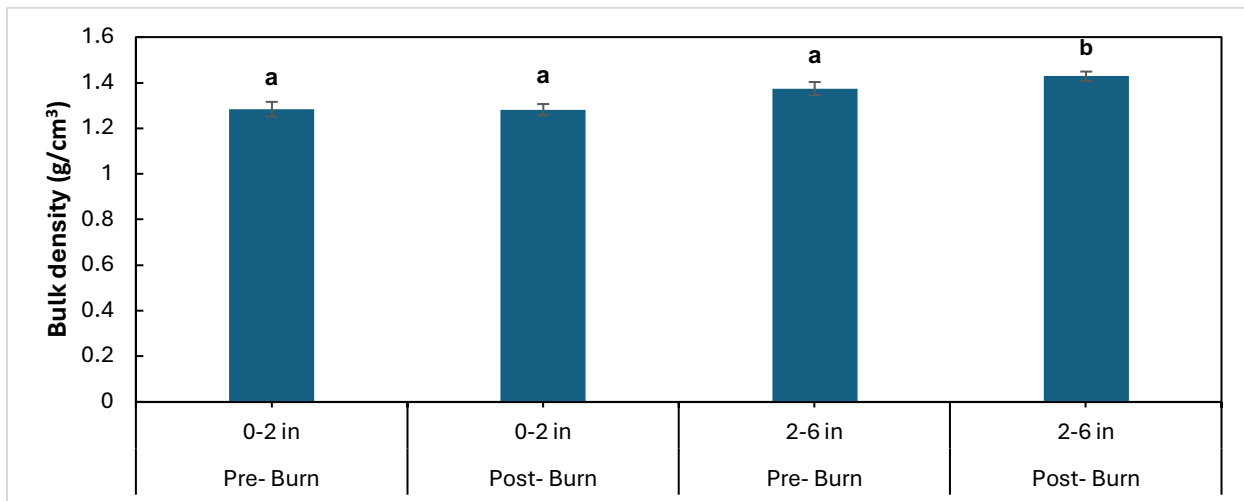


Fig. 2. Short-term response of soil bulk density to simulated wildfire in a semi-arid winter wheat-sorghum-fallow system in Hays, KS. Means with the same letter are not significantly different ($P < 0.10$).

Soil Penetration Resistance

Soil penetration resistance increased significantly after burning at both sampling depths (Fig. 3). Resistance increased from 0.90 to 1.22 MPa at the 0–2 in depth and from 1.18 to 1.74 MPa at 2–6 in depth, indicating greater soil strength and compaction following the burn. These increases are consistent with residue loss and post-burn structural changes that increase the susceptibility of semi-arid soils to compaction.

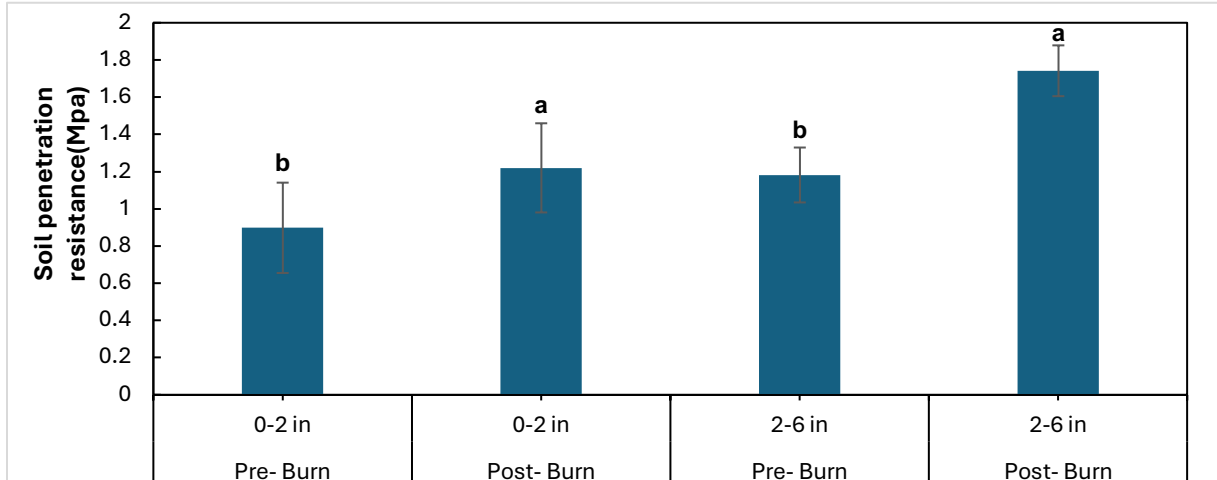


Fig. 3. Short-term response of soil penetration resistance to simulated wildfire in a semi-arid winter wheat-sorghum-fallow system in Hays, KS. Means with the same letter are not significantly different ($P < 0.10$).

Infiltration

Soil water infiltration declined significantly following burning (Fig. 4). Mean infiltration rate decreased from 6.44 in hr^{-1} under pre-burn conditions to 2.44 in hr^{-1} under post-burn conditions, representing a 62% reduction. This decline corresponds with observed increases in soil penetration resistance and bulk density, indicating reduced pore continuity and limited water movement through the soil profile following burning.

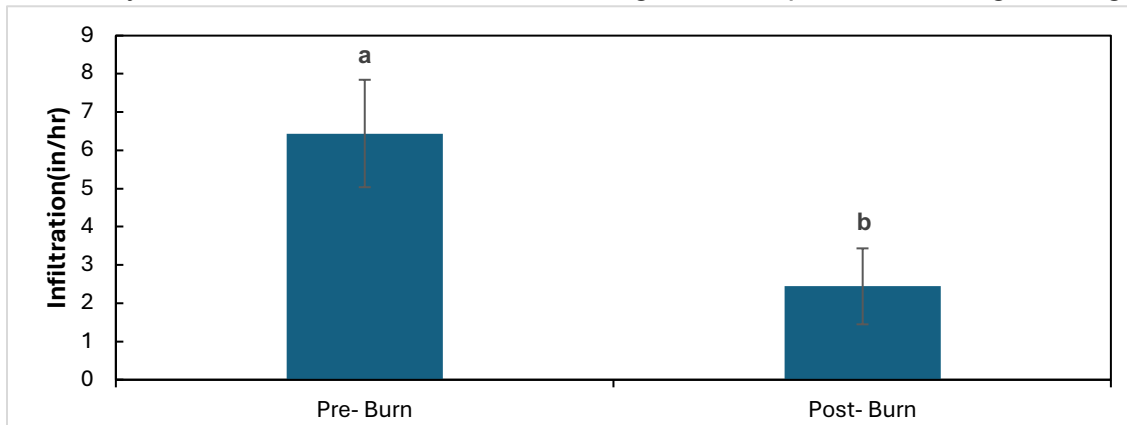


Fig. 4. Short-term response of infiltration rate to simulated wildfire in a semi-arid winter wheat-sorghum-fallow system in Hays, KS. Means with the same letter are not significantly different ($P < 0.10$).

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CARBON & NITROGEN TRANSFORMATION IN SOIL AFTER BIOSOLIDS OR INORGANIC FERTILIZER APPLICATION

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ABSTRACT

Biosolids are nutrient rich organic residues which could be a potential alternative to conventional fertilizers. However, their C and N mineralization rates vary depending on treatment processes and soil properties. A laboratory incubation was carried out to evaluate C and N dynamics in contrasting soils by quantifying gaseous losses and assessing N transformations between organic and inorganic pools. Soils collected from Texas (sandy clay loam, pH: 8.4) and Florida (sandy loam, pH: 7.6) were amended with electrolysis-treated biosolids (EGROW™), composted cattle manure, commercially available biosolid product (Top Choice), urea, and unamended control following a 2 × 4 factorial design with four replications. Initial results showed that top choice consistently produced higher CO₂ emissions across both soil types. NH₄⁺-N and NO₃⁻-N were measured on days 1, 7, 14, 28, 56, and 121. Headspace gases were collected to analyze CO₂, N₂O and CH₄ after 1, 2, 3, 5, and 9 days, and weekly afterward until the end of experiment. Compared to EGROW™, N₂O emissions in the Florida soil were not significantly different from urea but were 51.3% higher with Top Choice. In contrast, N₂O emissions were 202.5% higher with urea in Texas soil compared to EGROW™ but not significantly different from Top Choice. Urea resulted in greater NH₄⁻-N and NO₃⁻-N concentrations during the first two weeks compared to the biosolids in both soils. It is expected that the application of electrolyzed biosolids enhances C and N cycling and provide sufficient plant-available N, while minimizing gaseous N₂O losses compared to conventional fertilizers.

Keywords: Mineralization, nutrient cycling, biosolids, soil properties

OPTIMIZING P AND K MANAGEMENT IN WHEAT-SOYBEAN SYSTEM PRODUCTIVITY

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ABSTRACT

In Oklahoma, wheat-soybean double cropping has been used as a viable system to increase productivity, but its short growing seasons and high nutrient demand create unique phosphorus (P) and potassium (K) management challenges not addressed by Oklahoma's full season recommendation. This study evaluated the effects of P and K application timing (fall, winter, spring, summer) for double-crop soybean and P and K management rates on wheat-soybean productivity at Lake Carl Blackwell, Oklahoma (2024-2025). A split plot design with four replications evaluated four application timings and six P and K management rates (W Only, W + DC P, W + DC K, W + DC P&K, Control, and DC Only) using OSU soil test recommendations. Timing treatments were only applicable to the double-crop soybean, while P and K for wheat were all applied in the fall. The results revealed that P and K management rate, not application timing drove wheat-soybean productivity. Management rate significantly affected wheat yield ($p < 0.01$), and soybean yield ($p = 0.02$), while application timing had no significant effect on either crop yield ($p > 0.1$). Management rates with wheat fertilized significantly outperformed control. Soybean required direct P application for optimal yields, while adding K to soybean beyond wheat fertilization provided no yield benefit. W + DC P and K maximized system yield with W +DC P performing similarly. This initial findings suggest that adequate P and K management rate maximizes wheat-soybean productivity.

INTRODUCTION

Wheat-soybean double cropping has recently become an important form of intensifying agriculture in the Southern Great Plains especially in Oklahoma due to suitable weather patterns that allow the production of two different crops during one growing year (Reed et al., 2022). This system, which involves planting soybeans immediately after winter wheat harvest, maximizes land productivity and economic returns (Alori et al., 2017). The USDA-ERS estimated 1.81 billion bushels of winter wheat produced and 86.1 million acres of soybean planted in the USA in 2024 (USDA-ERS, 2025). The wheat-soybean rotation represents a significant part of U.S. agricultural production. However, the intensified nutrient demands and compressed growing season inherent to double cropping present unique challenges for phosphorus (P) and potassium (K) fertilizer management that remain inadequately addressed by current recommendations.

Current Oklahoma State University recommendations for P and K fertilization were developed for full-season crops and may not adequately meet the specific nutrient requirements of wheat-soybean double cropping systems. Research has consistently

demonstrated that double-crop soybeans grown after wheat are frequently limited by P and K availability, particularly when nutrient replacement is insufficient or when unfavorable environmental conditions restrict nutrient uptake (Parvej & Holshouser, 2025). The rapid nutrient cycling characteristic of successive cropping, creates nutritional demands that differ substantially from those of full-season systems. Furthermore, soil test predictions alone often fail to accurately reflect nutrient responsiveness in double-cropped soybeans due to temporal variability in nutrient availability and the complex interactions between soil fertility, application timing, and environmental factors (Yadav, 1998).

The objectives of this study were to evaluate the effect of P and K application timing on wheat and soybean grain yields and compare six fertilizer management rates for optimizing system-level productivity.

MATERIALS AND METHODS

This multi-year study being carried out at Lake Carl Blackwell Agricultural Research Station in Stillwater, Oklahoma addresses these knowledge gaps. This paper presents initial results from 2024-2025 season, using a split plot experimental design with four blocks. Each block was subdivided into four plots representing different fertilizer application timings, with each plot further divided into six subplots representing different fertilizer rate treatments, resulting in 96 total experimental units.

Experimental Treatments

Application Timing (Whole plot factor): Four fertilizer application timings were evaluated for the double-crop soybean component only (fall pre-wheat planting, winter wheat top-dress, spring wheat top-dress, summer pre-soybean planting). All wheat P and K applications were applied in the fall, irrespective of timing treatment to ensure adequate wheat nutrition.

Fertilizer Rate Treatments (Subplot Factor):

Wheat Fertilized Only (W Only): Wheat receives P & K, double-crop receives none.

Wheat Fertilized + Double-Crop P (W + DC P): Wheat receives P & K, double-crop receives P only.

Wheat Fertilized + Double-Crop K (W + DC K): Wheat receives P & K, double-crop receives K only.

Wheat Fertilized + Double-Crop P and K (W + DC P&K): Both wheat and the double-crop receive P & K.

Control: No P or K applied to either wheat or the double-crop.

Double-Crop Fertilized Only (DC only): Wheat receives no P nor K, the double-crop receives both P & K.

Phosphorus was applied as triple superphosphate (0-46-0) and potassium as muriate of potash (0-0-60) using broadcast application.

Data Collection

Site Characteristics and Soil Properties: Prior to treatment establishment, composite soil samples (10 cores, 0-6inch depth) were collected from each experimental block and analyzed at the Soil, Water and Forage Analytical Laboratory (SWAFL) at Oklahoma State University. Nitrogen fertilizer was applied uniformly across all blocks. All fertilizer rates varied by block and were based on OSU soil test recommendations to standardize nutrient availability relative to crop requirements.

Table 1. Initial soil fertility by experimental block.

Block	Soil Texture	pH	OM (%)	C (%)	N (%)	Soil P (ppm)	Soil K (ppm)
1	Medium	6.1	1.31	0.76	0.11	21.7	112
2	Coarse	5.8	0.98	0.57	0.10	33.5	133
3	Coarse	5.5	1.10	0.64	0.11	17.4	159
4	Coarse	5.6	0.89	0.52	0.10	17.2	108
Mean		5.8	1.07	0.62	0.11	22.5	128

Note: Fertility classifications based on OSU guidelines.

Crop Management

In December of 2024, winter wheat (cultivar Strad CL+) was sown at a rate of 75 lb/ac, with a row spacing of 7.5" and a seeding depth of 0.5". It was harvested in June of 2025. Seven days after the harvest of wheat, double-cropped soybeans (Asgrow 48XF3) were seeded at a rate of 160,000 seeds/ac, with a row spacing of 15" and a planting depth of 1.0". Soybean was harvested in October 2025.

Wheat and soybean grain yield was obtained using a small-plot combine to harvest approximately 18.3 m² from each of the subplots. The moisture content and protein concentration were determined by using the Near-Infrared Spectroscopy (NIR). The final yield was corrected to a standard of 13% moisture, and then expressed as bushels per acre (bu/ac).

Statistical Analysis

Data were analyzed using R version 4.4.1 with lme4, lmerTest, ggplot2, and emmeans packages. Type III ANOVA was performed using linear mixed-effects models. Timing and rate were modeled as fixed effects, while block, block × timing, and residual error were modeled as random effects. Post-hoc pairwise comparisons used Tukey's HSD ($\alpha = 0.1$). Assumptions were verified using residual plots and Shapiro-Wilk tests.

RESULTS

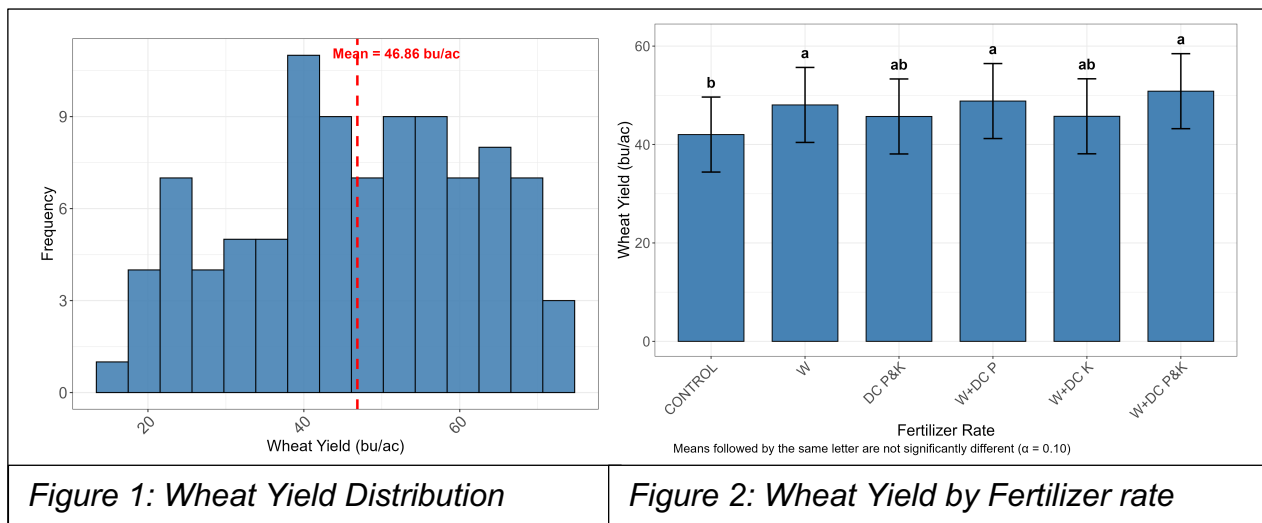
Wheat Yield: Fertilizer management rate significantly affected wheat yield. Mean wheat yield was 46.86 bu/ac. Mean separation revealed three distinct groupings among fertilizer management rates (Figure 2). The top-performing group (W+DC P&K, W+DC P, and W

alone) yielded 48.0-50.8 bu/ac, representing up to 21% increase over the control (42.0 bu/ac). The DC P&K and W+DC K rates showed intermediate performance (45.7 bu/ac each), while the control produced the lowest yield.

Table 2. Analysis of variance for wheat yield in wheat-soybean system.

Source	Df	F-value	p-value
Timing	3	1.98	0.19
Rate	5	4.91	< 0.01***
Timing × Rate	15	1.19	0.30

Note: *** $p < 0.001$; Model statistics: Whole plot CV = 9.15%; Subplot CV = 11.82%; Marginal $R^2 = 0.08$; Conditional $R^2 = 0.9$



Similar to wheat, soybean yield was significantly influenced by fertilizer management rate. Mean soybean yield was 32.7 bu/ac. Mean separation revealed two groupings among fertilizer strategies for soybean yield (Figure 4). The DC P&K strategy produced the highest yield at 34.9 bu/ac, representing a 17% increase over the control (29.8 bu/ac). This strategy, along with W+DC P&K (34.1 bu/ac) and W+DC P (34.0 bu/ac), formed the top-performing group. The W+DC K and W strategies showed intermediate performance (32.0 and 31.7 bu/ac, respectively), while the control produced significantly lower yields than the top three strategies. The absence of significant timing effects for both crops allows growers to have operational flexibility in scheduling P and K applications based on weather, labor availability, and equipment logistics without yield penalty.

Table 3. Analysis of variance for soybean yield in wheat-soybean system.

Source	Df	F-value	p-value
Timing	3	0.97	0.45
Rate	5	3.00	0.02*
Timing × Rate	15	1.05	0.42

Note: * $p < 0.05$; Model statistics: Whole plot CV = 15.4%; Subplot CV = 13.6%; Marginal $R^2 = 0.19$; Conditional $R^2 = 0.6$

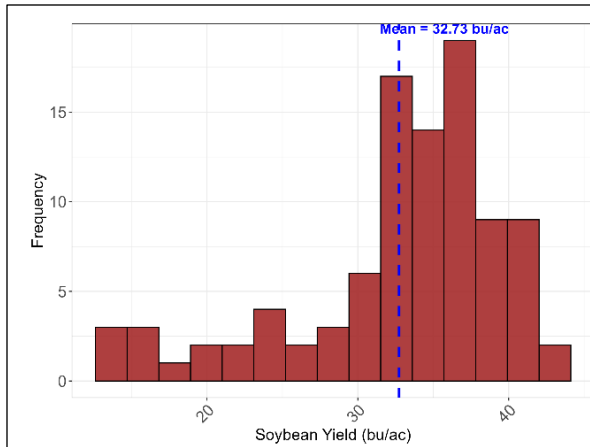


Figure 3: Soybean Yield Distribution

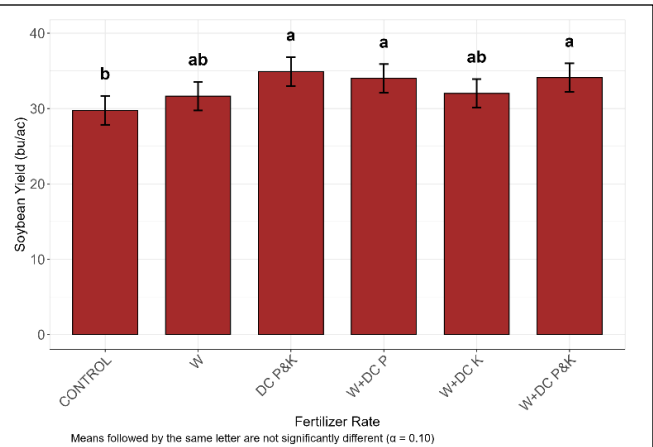


Figure 4: Soybean Yield by Fertilizer Rate

System-level Productivity

System-level productivity, evaluated by summing wheat and soybean grain yields, ranged from 71.8 bu/ac (control) to 84.9 bu/ac (W+DC P&K), representing an 18% increase through appropriate nutrient management. The consistent pattern of significant rate effects, non-significant timing effects, and absent timing × rate interactions (Table 2 and 3) across both crops highlights the primacy of fertilizer management rate over application timing. Although both crops responded to fertilization, numerically higher soybean yields were observed under DC only (34.9 bu/ac), while the highest system-level productivity (84.9 bu/ac) was observed under (W + DC P&K), with P nutrition for soybean (W + DC P) performing similarly. These pattern suggest the importance of whole-system nutrient management. Under-fertilization resulted in yield penalties of 4-6 bu/ac for wheat, 3-5 bu/ac for soybean, and 13.1 bu/ac at the system level, highlighting the potential importance of adequate P & K for crop productivity.

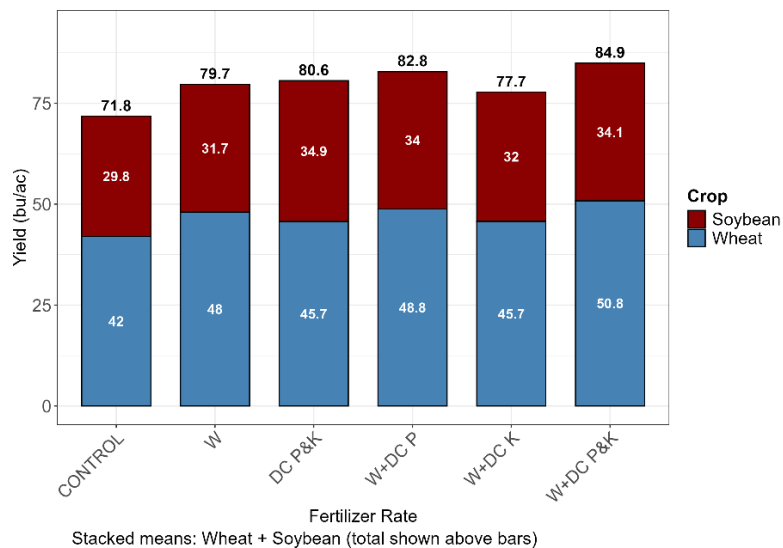


Figure 5: System Productivity (Combined Wheat and Soybean)

Fertilizer management rate, not application timing, drove wheat-soybean productivity, as evidenced by significant rate effects, non-significant timing effects, and the absence of timing × rate interactions. This operational flexibility suggests that producers can schedule fertilizer applications based on weather conditions, labor availability, and equipment logistics without yield penalty. Model performance differed between crops, with wheat explaining 89% of variation (CV = 9-12%) compared to soybean's 67% (CV = 14-15%), reflecting greater environmental sensitivity in double-crop soybean due to late planting, compressed growing season, and potential moisture stress. Future research will examine multi-year consistency of these patterns, evaluate residual nutrient effects across cropping cycles, and incorporate soil moisture at multiple depth as a covariate to account for water availability effects on nutrient response.

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MAIZE RESPONSE TO NITROGEN AND SULFUR FERTILIZATION RATES

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ABSTRACT

Due to reduced atmospheric deposition and advancements in agronomic management, sulfur (S) deficiency has become an increasing concern in maize production systems. Because S plays a fundamental role in nitrogen (N) metabolism, S availability may influence maize yield response to N fertilization. This study evaluated maize response to N and S fertilization rates across six locations in Oklahoma. Field experiments were conducted using a randomized complete block design with 14 treatments and four replications per site. Nitrogen was applied at six rates (0, 45, 65, 85, 105, and 115% of estimated yield goal), while S was applied at 0, 10, or 20 lb S ac⁻¹. Grain yield responses were primarily driven by N application, with significant positive responses observed across environments ($\alpha = 0.1$). In contrast, S fertilization resulted in minimal and inconsistent yield responses. The addition of S did not consistently alter N response curves or significantly increase yield at most locations. Significant yield increases associated with a S application were observed only at the highest N rate at two sites. Weak correlation between S treatments and grain yield suggests S was not a yield-limiting factor under the evaluated conditions. Environmental conditions during the growing season, including above-average rainfall and warm temperatures, likely enhanced in-season nutrient mineralization. These are preliminary findings, continued research during the 2026 growing season will further evaluate the consistency and significance of the observed responses.

SHEEP GRAZING PREFERENCE AND NUTRIENT CYCLING IMPLICATIONS AMONG COVER CROP SPECIES

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ABSTRACT

A replicated small-plot study was conducted in San Angelo, TX, using a randomized complete block design (5 × 20 ft plots; four replications) to evaluate forage yield, sheep grazing preference, and relative herbage removal among winter cover crop species and cultivars, including vetch, peas, turnips, oats, rye, triticale, barley, and wheat. Pre- and post-grazing biomass measurements and overhead imagery were used to quantify canopy reduction and grazing selection. Buckaroo barley produced the greatest herbage mass (3346 kg ha⁻¹), exceeding other cereal grains (mean = 1931 kg ha⁻¹) and legumes (mean = 744 kg ha⁻¹). Despite high biomass production, Buckaroo barley was among the least preferred species, exhibiting 66% less canopy reduction than wheat and 48% less than other winter cereals. Wheat and oats achieved the most favorable balance between biomass production and grazing preference, resulting in the greatest total herbage mass removed. These findings highlight the importance of considering both forage yield and animal preference when selecting cover crop species for integrated crop–livestock systems. Species that optimize both biomass production and grazing utilization may enhance nutrient redistribution efficiency and overall system performance.

INTRODUCTION

The vast and interspersed livestock and crop industries of Texas lend opportunity for livestock integration to benefit regional agricultural systems. Texas leads sheep production in the U.S. and small ruminant integration in crop systems has become an appealing opportunity in recent years due to strong meat markets and generally poor commodity crop markets. Many winter cover crops are likely suitable forages, and challenges of nutrient immobilization could be (at least partially) mitigated by ruminant digestion and excretion. Information is limited, however, regarding grazing preference and nutrient implications of different species.

MATERIALS AND METHODS

Cover crop species/cultivars were evaluated in a replicated small-plot trial at San Angelo, TX for forage yield, sheep grazing preference, and relative herbage removal. Treatments included hairy vetch (*Vicia villosa*), wooly pod vetch (*Vicia villosa* ssp.

dasycarpa), Austrain winter peas (*Pisum sativium*), purple-top turnips (*Brassica rapa subsp. rapa*), 'Bob' oats (*Avena sativa*), 'Elbon' rye (*Secale cereale*), 'Trical 813' triticale (\times *Triticosecale*), 'Buckaroo' barley (*Hordeum vulgare*), and 'Razor' wheat (*Triticum aestivum*). Treatments were arranged in a randomized complete block design composed of small plots (5 × 20 ft) with 4 replications. Forage biomass was sampled and overhead imagery of the plots were collected pre- and post-grazing with sheep.

RESULTS AND DISCUSSION

Buckaroo barley yielded greater herbage mass (3346 kg ha⁻¹) than the other cereal grains (mean = 1931 kg ha⁻¹) and legumes (mean = 744 kg ha⁻¹), but was among the least preferred, with 66% and 48% less canopy reduction from the sheep compared to wheat and the remaining winter cereals, respectively (Figure 1).

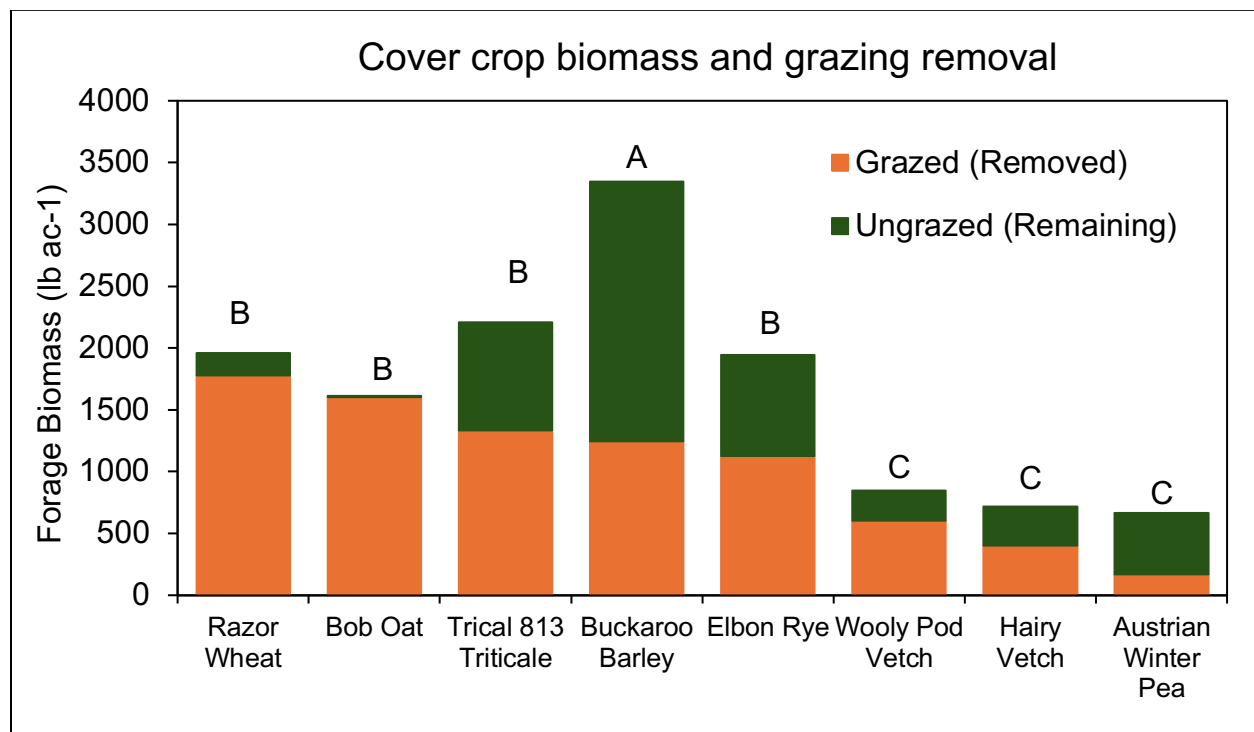


Figure 1. Cover crop effect on total, grazed, and ungrazed forage.

Wheat and oats represented the greatest herbage mass grazed (Figure 1), indicating the most advantageous balance between biomass production and grazing preference. Measured biomass reductions likewise aligned with imagery-derived measurements of canopy reduction (Figures 2 and 3), associating overall canopy reduction with forage utility. Beyond implications of single-species planting, these findings are anticipated to help inform optimum species mixtures for grazing potential and cover crop function.

Entry	Before	After	Green-Leaf Index Change
Purple Top Turnip			
Bob Oat			
Woolly Pod Vetch			
Austrian Winter Pea			
Razor Wheat			
Balansa Clover			
Elbon Rye			
Hairy Vetch			
Silver River Sweetclover			
Buckaroo Barley			
Trical 813 Triticale			

Figure 2. Cover crop imagery before vs. after sheep grazing and change in green-leaf index.

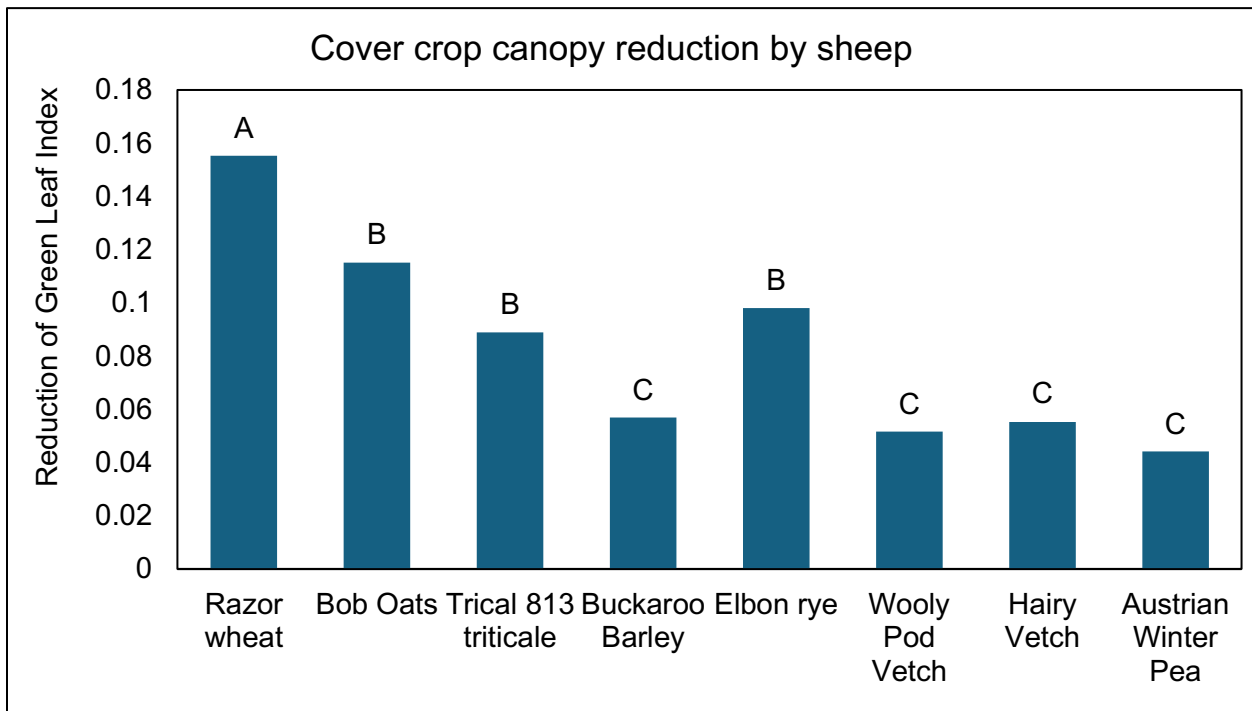


Figure 3. Cover crop variety impact on green-leaf index change pre- and post-grazing.

EVALUATING THE EFFECTS OF CHARGING AND INOCULATING BIOCHAR DERIVED FROM INVASIVE SPECIES EFFECTS ON GROWTH AND YIELD OF CROPS AND SOIL HEALTH IN OXISOL AND MOLLISOL SOILS

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ABSTRACT

Invasive species such as *Leucaena leucocephala* are encroaching on arable lands in Hawai'i, affecting agricultural productivity. Converting this biomass into biochar offers a multifaceted solution for eradication, arable-land reclamation, and production of a high-quality sustainable soil amendment that enhances soil health and crop yields. Although biochar is a carbon-rich material with proven benefits, the necessity of pre-application inoculation/charging (e.g., with biology and nutrients) remains unclear. Here, biochar was produced from *Leucaena* wood using a small-scale retort kiln. Eight treatments were tested across Oxisol and Mollisol soils in greenhouse pot trials at the University of Hawai'i: (1) soil alone (control), (2) soil + biochar, (3) soil + compost, (4) soil + biochar-assisted compost, (5) soil + biochar + fish emulsion, (6) soil + biochar + compost, (7) soil + biochar + compost + fish emulsion, and (8) soil + biochar-assisted compost + fish emulsion. Biochar and compost were applied at the rates of 5 and 10 t/ac, respectively. Biochar charging/inoculation was performed 3 days before planting, with 64 pots established (2 soils × 8 treatments × 4 replicates) using beets and pak choi as test crops; measurements included fresh/dry biomass (yield), leaf chlorophyll content, tissue nutrient concentrations, and soil health indicators (pH, CO₂). Charged/inoculated biochar treatments increased the crop fresh weight by ~50% and leaf chlorophyll content, 35% and 41% for beet, and 49% and 41% for pak choi under Oxisol and Mollisol soils, respectively compared to the control. In both soil types, nutrient uptake increased up to 95% for N, 200% for P, and 75% for K compared to the control. Soil pH increased by 45% and 20% under Oxisol and Mollisol, respectively, compared to the control. CO₂ respiration rate increased by 75% in both soil types compared to the control. These results confirm *Leucaena*-derived biochar is an effective amendment and emphasize the importance of charging/inoculating the biochar for optimal crop productivity and soil health in Hawaiian agroecosystems.

INTRODUCTION

In Hawai'i, invasive plant species like *Leucaena leucocephala*, commonly known as haole koa, pose serious challenges to agricultural land. These plants spread quickly, producing vast amounts of seeds, forming dense thickets, and outcompeting native vegetation. As a result, they reduce farmland availability and threaten food security in the islands (Graebner et al., 2012). Globally, invasive species present major risks to

agriculture. A study of 1,300 invasive species across 124 countries found they significantly reduce crop yields and jeopardize food security (Paini et al., 2016). For Pacific islands, food security and self-sufficiency are top priorities. Hawai'i, for instance, imports about 85–90% of its food, with reserves typically lasting only two weeks at any time (Leung and Loke, 2008).

Biochar is a stable, carbon-rich material produced by pyrolyzing organic feedstocks under low-oxygen conditions, and it has emerged as a promising soil amendment (Berek, 2015). It is valued for its large surface area (Figure 1), which enhances soil nutrient retention, improves water-holding capacity, and provides a habitat for beneficial soil microorganisms (Leng et al., 2021). Previous research has demonstrated that biochar application can increase soil water-holding capacity (Laird et al., 2010; Silber et al., 2010), release plant nutrients into the soil (Smider and Singh, 2014), retain nutrients and prevent leaching (Berek and Hue, 2013), reduce greenhouse gas emissions (Kammann et al., 2011), promote beneficial soil microorganisms (Xu et al., 2014), remove heavy metals and organic pollutants from soil or water (Uchimiya et al., 2012), and enhance plant resistance to diseases while promoting growth (Elmer and Pignatello, 2011).

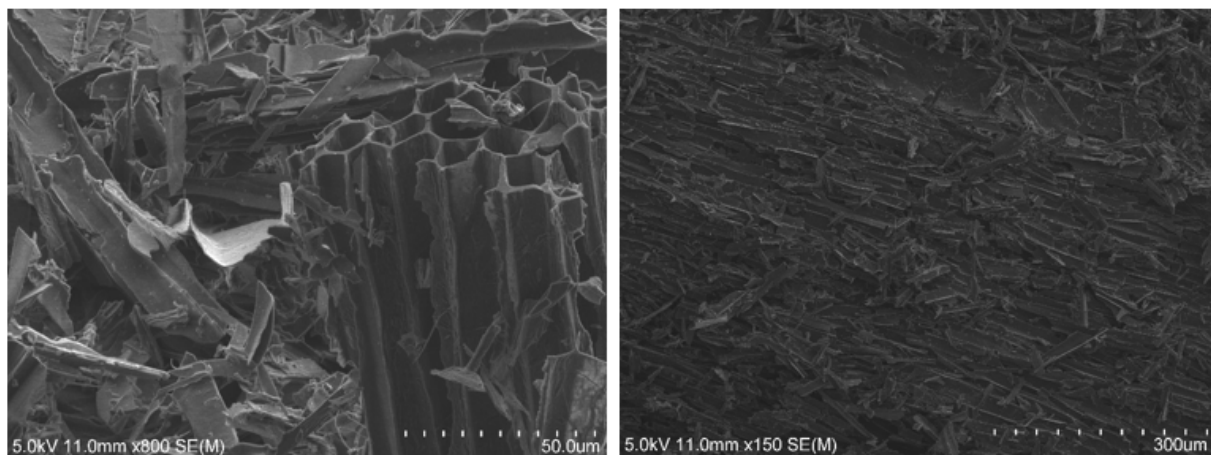


Figure (1): Microscopic pictures of biochar particles showing high surface area.

Composting offers a sustainable way to recycle organic waste into beneficial soil amendments, and Hawai'i's year-round growing season provides abundant composting materials. Applying organic materials like compost improves soil properties and crop yields. However, using invasive species in compost or animal feed carries risks, typical composting or digestion conditions often fail to eliminate seed viability (Pan, et al., 2022). In contrast, producing biochar through pyrolysis effectively eliminates seed viability, preventing re-establishment of invasive plants (Namaswa et al., 2023; Woolf et al., 2010). Using invasive species to process into biochar is expected to come with many benefits, including reclaiming arable lands and supporting the invasive species eradication effort,

producing high-quality sustainable soil amendments, and improving soil and crop productivity.

Affordable biochar production equipment, like the steel-drum retort kiln systems used in this experiment, can be constructed or purchased locally at a fraction of the cost of commercial kilns. This project establishes a proof of concept using *Leucaena leucocephala* as a model invasive species, with results intended to be used across other problematic invasives. The central question this study investigates is: Should farmers inoculate (load with microorganisms) and/or charge (load with nutrients) biochar prior to field application to maximize its benefits in agricultural systems? This study investigates the dual benefits of converting invasive *Leucaena* biomass into biochar using low-cost, DIY fabricated steel-drum pyrolysis systems and evaluate the effectiveness of charging and inoculating the locally produced biochar prior to applying to soils on pak choi and beetroot growth and yield and soil health parameters under Oxisol and Mollisol soils.

MATERIALS AND METHODS

Two pot trials were conducted in 2025 to evaluate charging and inoculating biochar on the growth, yield/pot, and tissue nutrient content of beet (*Beta vulgaris*) variety Merlin and pak choi (*Brassica rapa* subsp. *Chinensis*) variety Mei Qing Choi, and soil health of Oxisol and Mollisol soils. Oxisol soil was collected from the Poamoho Research Station, while Mollisol soil was collected from Waimanalo Research Station. Biochar was produced at the Waimanalo Research Station using *leucaena*. The biochar was prepared using retort kiln pyrolysis chambers (figure 2). The pyrolysis chamber is made of 2 steel drums (60-L and 210-L). The inner 60L (16 gallon) steal drum stores the wood to be turned into biochar, and the outer 210L (55 gallon) barrel stores wood for combustion to heat the inner chamber. The Biochar Assisted Compost (BAC) was produced with locally produced compost at Hawaiian Earth Works Products (<https://hawaiianearth.com>) mixed at 5% biochar of the compost pile volume. Eight treatments were determined to answer the biochar charging and inoculation need questions as described below.

T1: Soil only: Control.

T2: Soil + Biochar.

T3: Soil + Compost.

T4: Soil + Biochar assisted compost (BAC).

T5: Soil + Biochar + Compost.

T6: Soil + Biochar + Fish Emulsion.

T7: Soil + Biochar + Compost + Fish Emulsion.

T8: Soil + Biochar + BAC + Fish Emulsion.

Note: Biochar was applied at 12,500 kg/ha (5 t/ac) and compost/BAC were applied at the rate of 25,000 kg/ha (10 t/ac). Treatments 2-8 were the amendments (biochar, compost,

BAC, FE based on each treatment) were incubated together in sealed ziplock bags for 3 days, then thoroughly mixed into the soil based on each treatment individually.

Quality assessment based on the International Biochar Initiative (IBI) standard were conducted by the Soil Control Lab (<https://www.controllabs.net/>) on the locally produced biochar compared to commercially available biochar brand (<https://www.fbn.com/direct/product/cool-terra-organic/specimen-label>) showed they have very similar quality values in total carbon content and surface area (Figure 3), ash content, and pH (Figure 4). A total of 64 (8 treatments X 4 replicate X 2 soils) 2-gallon pots were used in the trials for each crop. The 8 treatments X 2 soils pots were distributed randomly on 2 greenhouse benches, divided into 4 blocks. Beet seeds were planted directly into each pot at the rate of 3 seeds/pot. Then plants were thinned to 1 plant after germination. Pak choi seeds were planted into 50-cell trays and then transplanted after producing true leaves at the rate of 1 seedling per pot. Nitrogen fertilizer was applied at the rate of 50 and 100 kg N/ha using 6-4-6 Sustane organic fertilizer for beet and pak choi, respectively. The fertilizer was calculated based on the soil weight in each pot. An overhead irrigation system was utilized for both trials.

Leaf relative chlorophyll content using SPAD Minolta meter was measured for both crops, and all treatments and replicates prior to harvest. Beetroot and pak choi fresh weights were measured at harvest. Beetroot and pak choi were dried using a conventional oven for 72 hours at 70°C, then percent dry weight was recorded. Due to the small amount of dry biomass collected, a composite sample for each treatment was submitted for chemical analysis to measure nitrogen (N), phosphorus (P), and potassium (K) tissue content. Soil samples were collected from each pot to measure soil pH using pH/EC combo meter and CO₂ respiration rate using Solvita Kit. Analysis of variance (ANOVA) for RCBD was performed using Statistix Software V. 10 (<https://www.statistix.com>) to evaluate the effect of the 8 treatments on the study parameters (plant growth and soil health) and determine significance level.

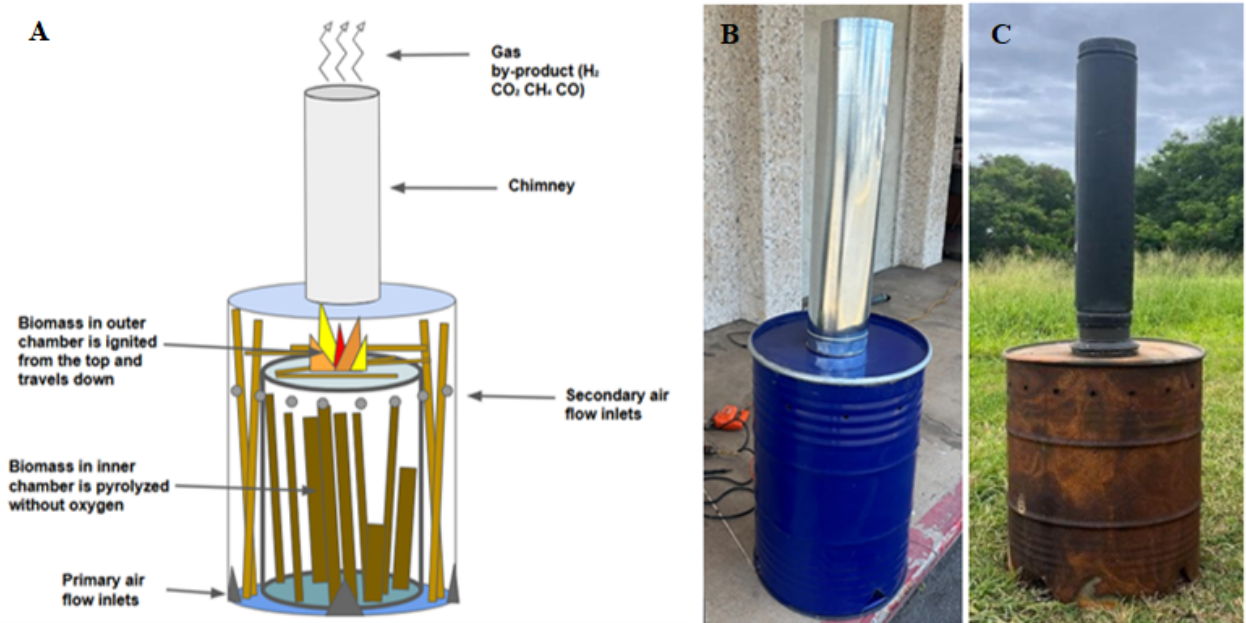


Figure (2): A diagram (A), the actual retort kiln used in the trials before the 1st burn (B), and the retort kiln after multiple burning (C).

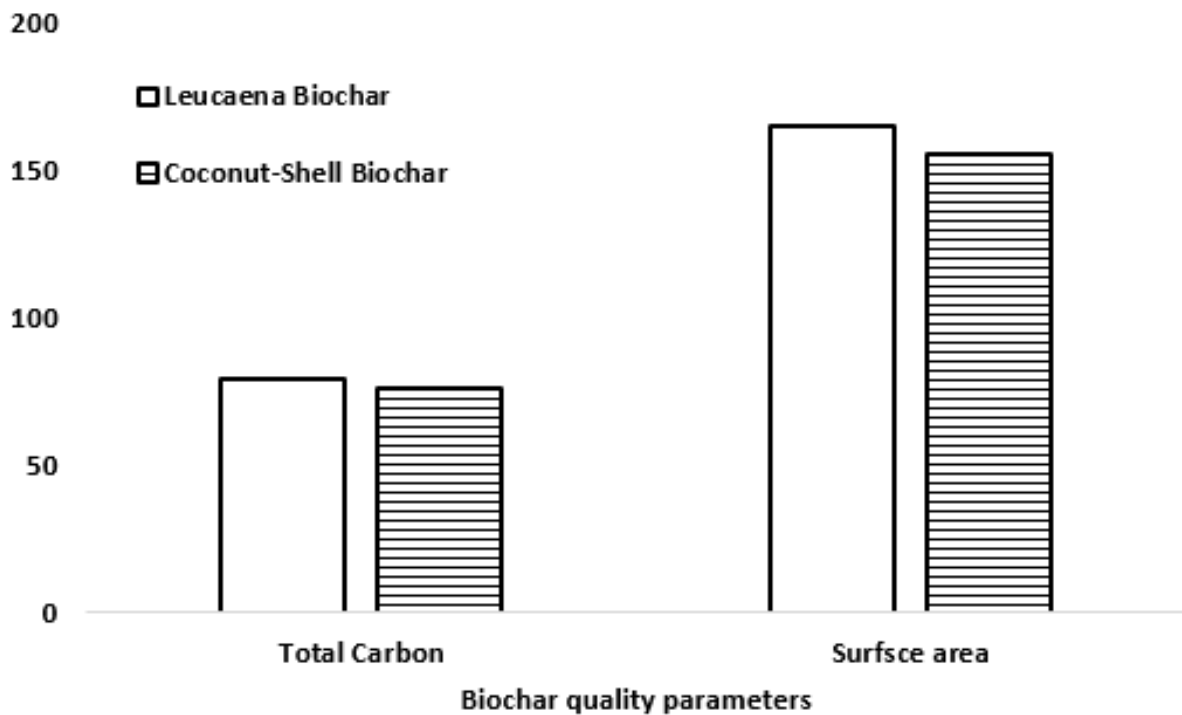


Figure (3) Total carbon (%) and surface area (m²/g) in the locally produced vs. commercial biochar based on the IBI standard.

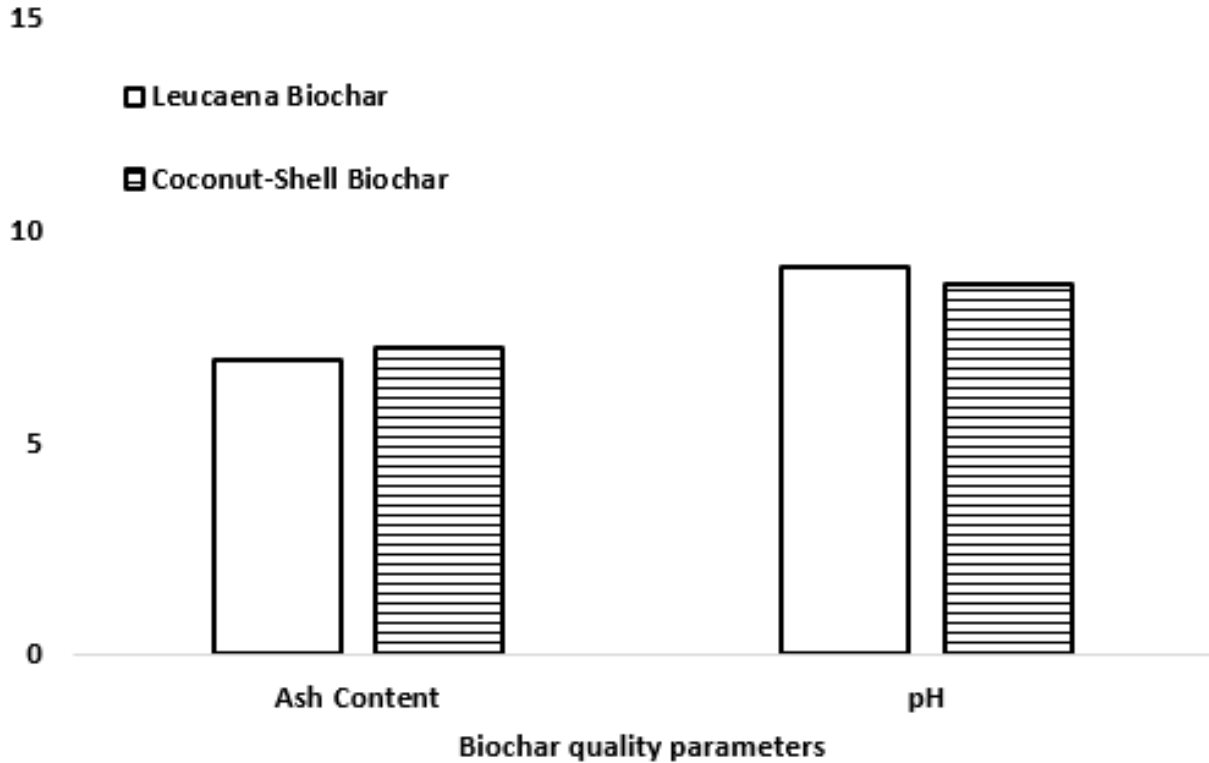


Figure (4) Ash content (%) and pH in the locally produced vs. commercial biochar based on the IBI standard.

RESULTS AND DISCUSSION

Statistical analysis:

The analysis of variance results showed that pak choi and beetroot fresh and percent dry weights have shown a highly significant ($p > 0.01$) response to the study treatments. However, relative chlorophyll content showed significant ($p > 0.05$) response to the study treatments. Both soil health parameters (soil CO₂ respiration rate and pH) showed a significant ($p > 0.05$) response to the study treatments based on the ANOVA results.

Crop growth and yield:

Both pak choi and beetroot showed a steady increase in plant growth from the control treatment (T1-soil only) to T8 (Soil + Biochar + BAC + Fish Emulsion). The results showed that charging and inoculating the biochar prior to application to soil have benefitted the study crops (Figure 5). Similar growth pattern and response were observed for both crops under the two soil types. Additionally, the results showed that although all biochar and compost application treatments were better than soil only (T1-control) treatment, but the charged and inoculated biochar (T4-T8) treatments performed better than biochar and compost application only (T2 and T3).



Figure (5) pak choi (upper) and beetroot (lower) harvested under the 8 treatments under Oxisol soil.

Charged/inoculated biochar treatments substantially increased the crop fresh and percent dry weight (Figure 6-9). Pak choi fresh weight increased by up to 81% and 65% compared to the control under Oxisol and Mollisol, respectively (Figure 6). The fresh weight of beetroot increased by up to 83% and 50% compared to the control, under Oxisol and Mollisol, respectively (Figure 7). Pak choi dry weight increased by up to 83% and 50% compared to the control under Oxisol and Mollisol, respectively (Figure 8). Beetroot dry weight increased by up to 26% and 31% compared to the control under Oxisol and Mollisol, respectively (Figure 9). The results is an agreement with what Asirifi, et al (2025) reported of combining biochar and compost showed significant results in soybean growth and yield. Also, Berek (2015) reported that biochar+compost application improved the growth and biomass in pak choi. Antonangelo, et al (2021) have reported in their review that various crops have shown significant response to the application of biochar-compost combination compared to biochar only or control (soil only).

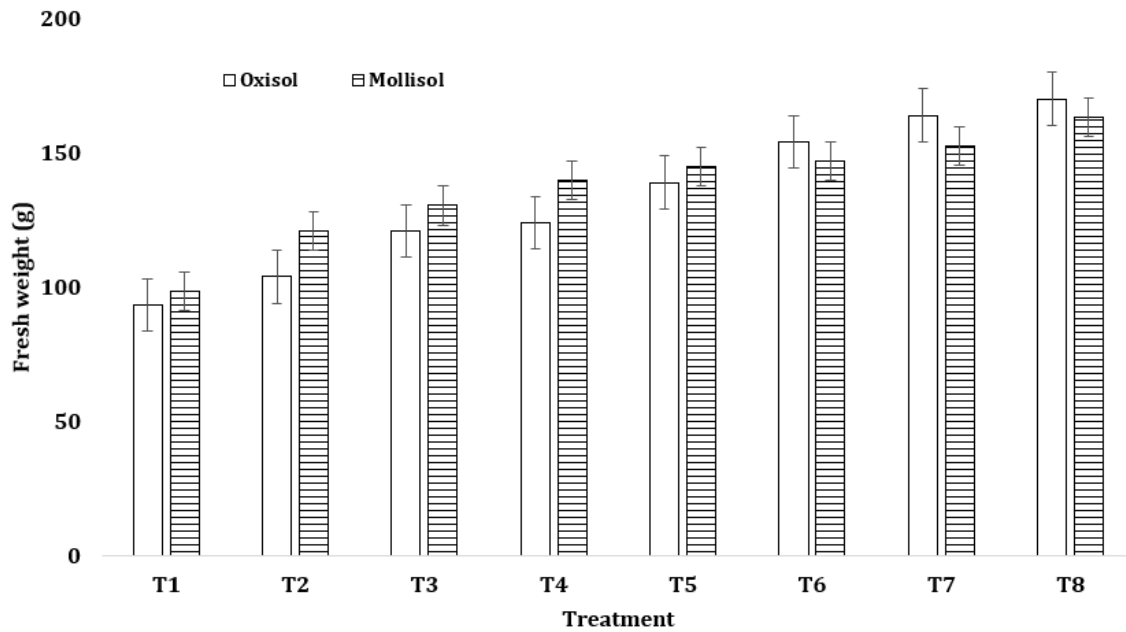


Figure (6) Fresh weight (g) of pak choi under the 8 treatments and soil types.

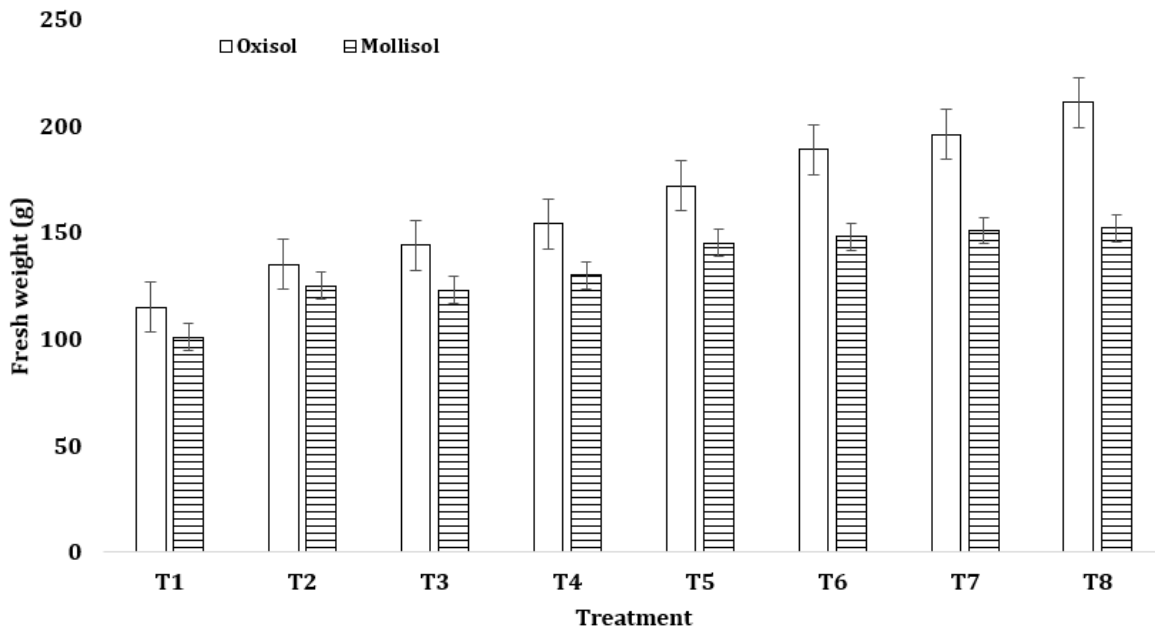


Figure (7) Fresh weight (g) of beetroot under the 8 treatments and soil types.

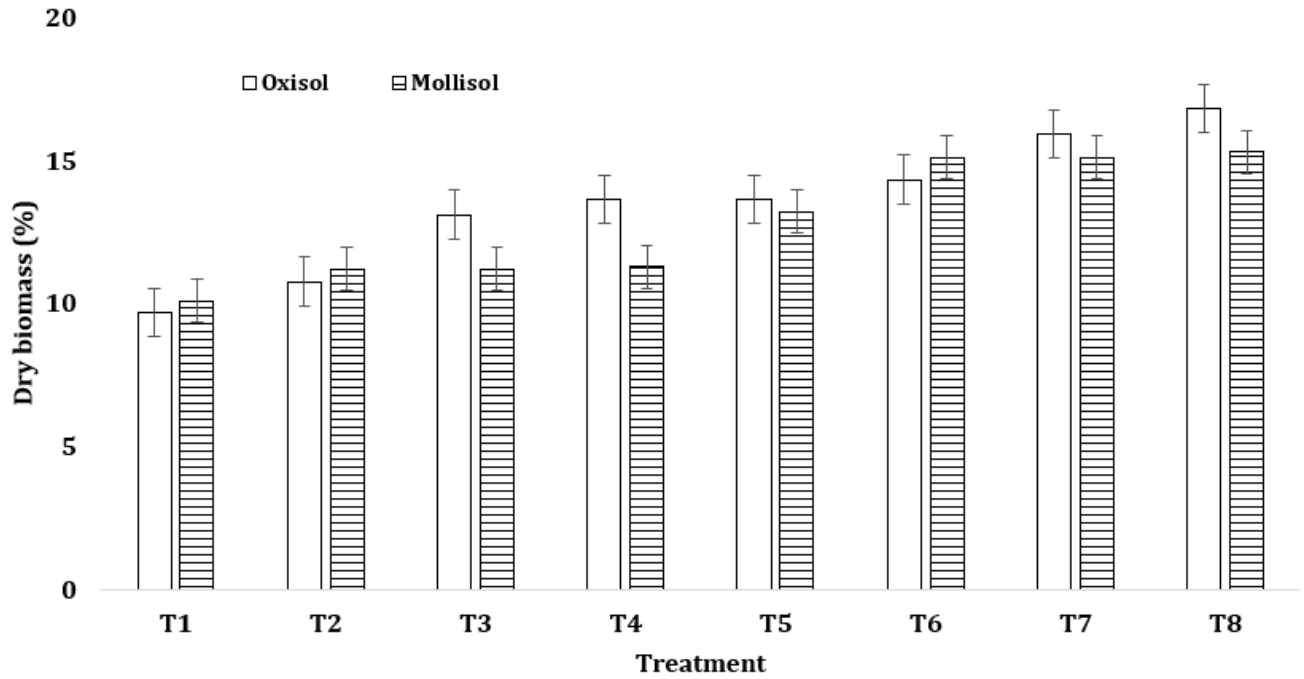


Figure (8) Percent dry weight (% DW) of pak choi under the 8 treatments and soil types.

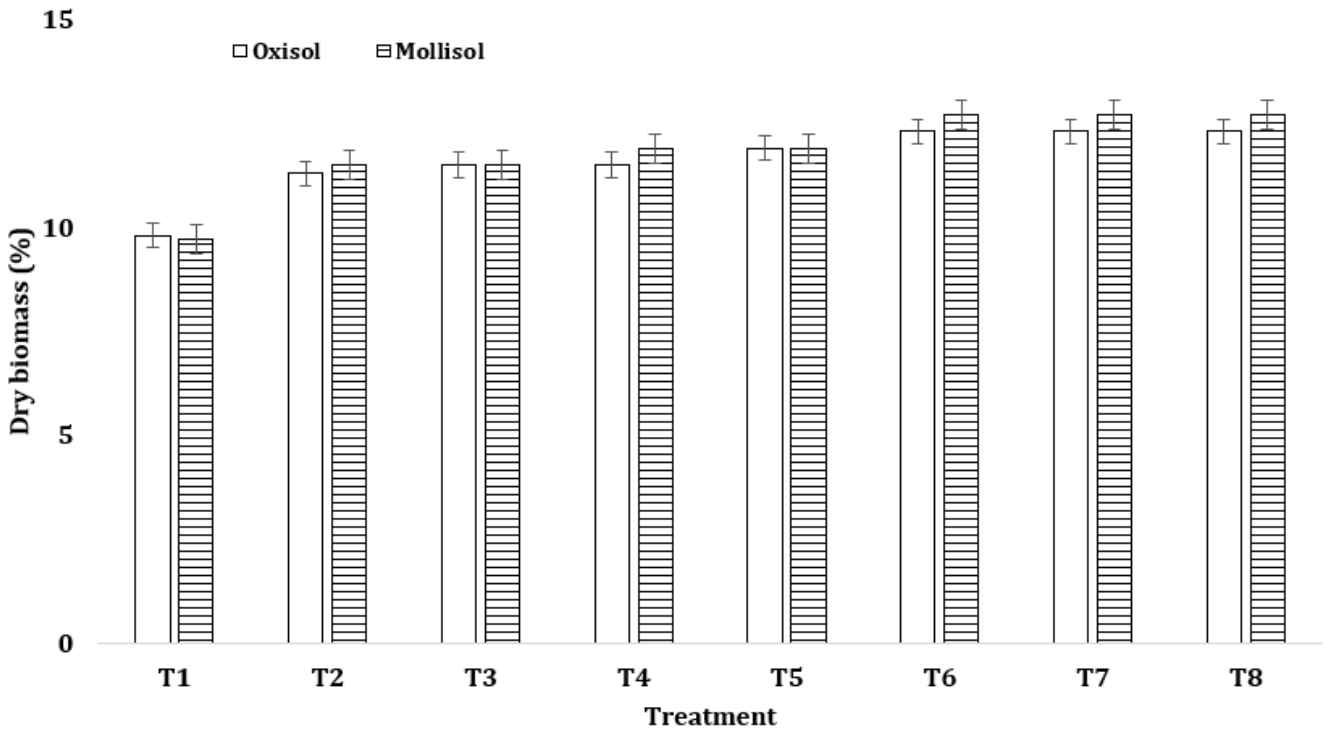


Figure (9) Percent dry weight (% DW) of beetroot under the 8 treatments and soil types.

Leaf chlorophyll content also increased by up to 35% and 41% for beetroot, and 49% and 41% for pak choi under Oxisol and Mollisol soils, respectively (Figure 10-11). These findings suggest that the charged/inoculated biochar treatments increased overall growth of the crops for many reasons, with some being the increased nutrient availability and improved soil health due to the treatments. The increased nutrient availability would explain the increased fresh and dry weight of the crops. With more nutrients available, the crops were able to grow more and faster in a faster time than the crops with no or fewer amendments. The increased leaf chlorophyll content also suggests that there was increased nitrogen available to the plant in the soil which is likely due to the treatments used. The leaf chlorophyll content was calculated using a SPAD meter, which stands for Soil Plant Analysis Development and is used to allow growers to estimate the nitrogen availability in the soil. So, with a higher SPAD reading, it is showing that there is more nitrogen available for the plant to use and uptake. The results are in agreement with Bekchanova, et al (2024) study which reported improved crop growth under biochar application. Also, Agegnehu, et al (2015) reported that peanut crop leaf chlorophyll content improved significantly under biochar-compost application compared to biochar only.

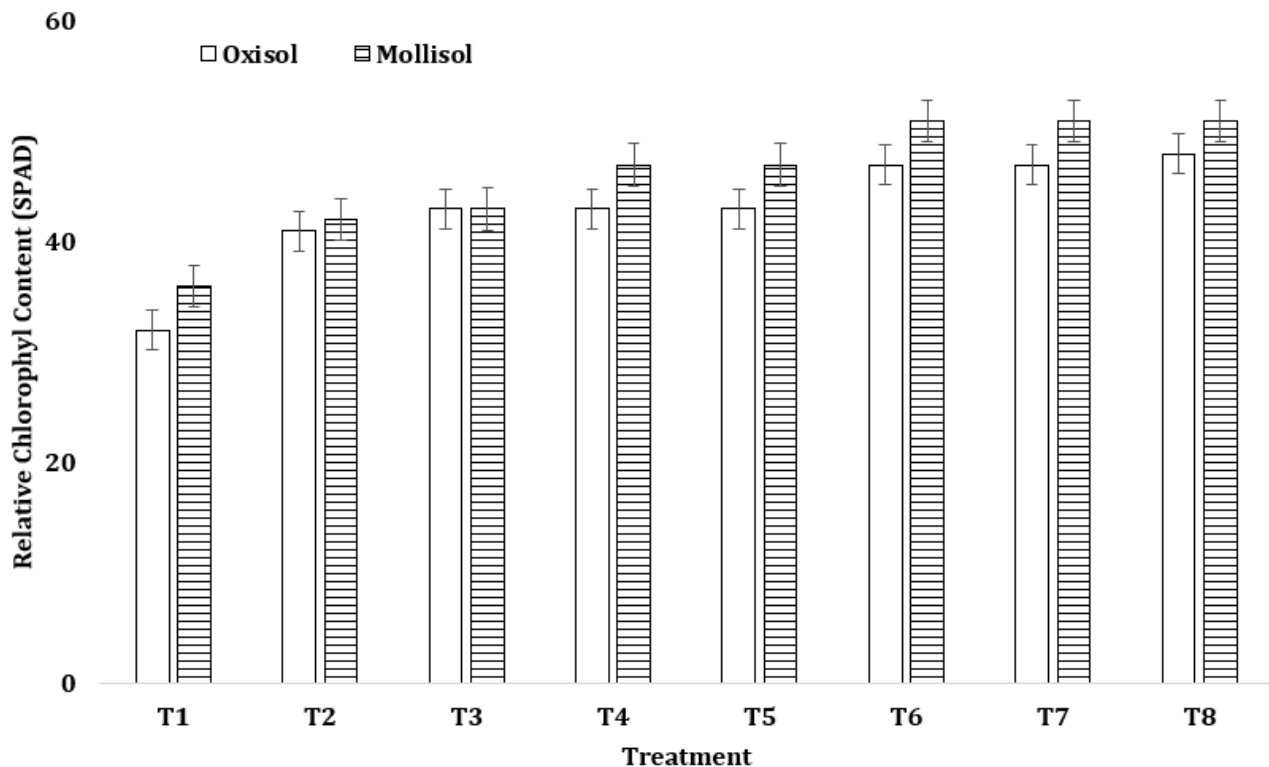


Figure (10) Relative chlorophyll content in pak choi leaves under the 8 treatments and soil types.

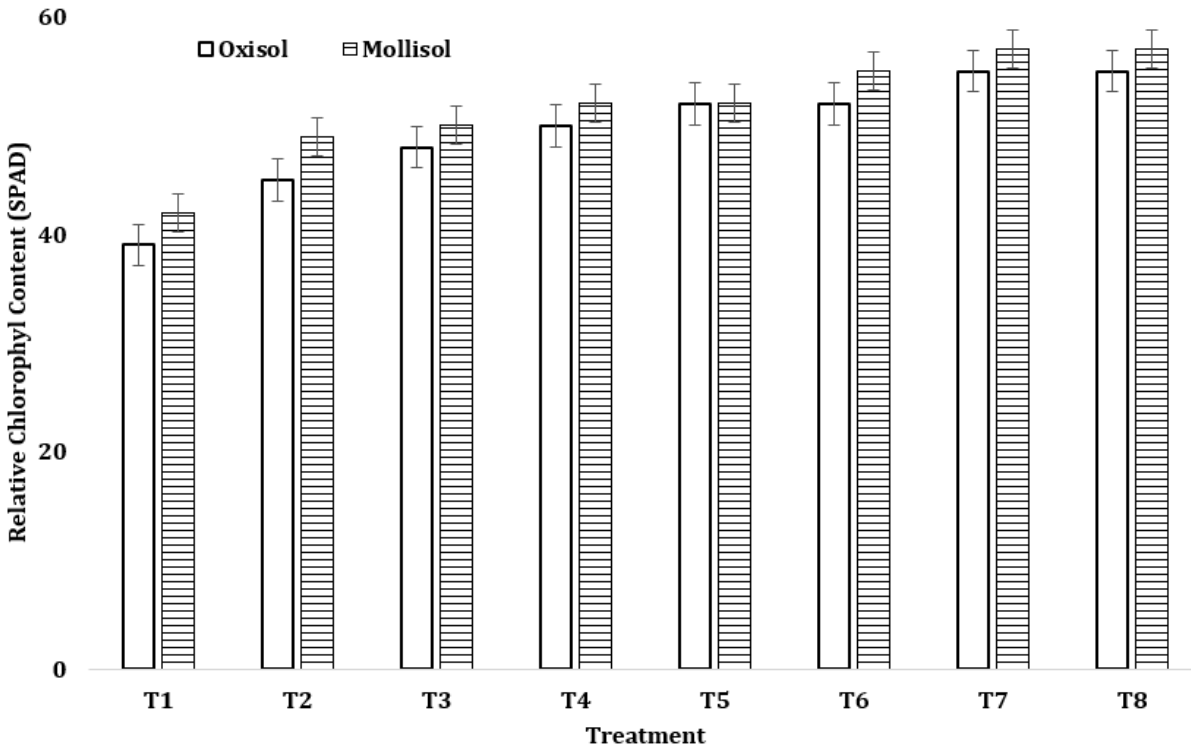


Figure (11) Relative chlorophyll content in beetroot leaves under the 8 treatments and soil types.

Nutrient uptake also improved under charged/inoculated biochar treatments compared to the control (soil only) and biochar only, The highest nitrogen (N%), phosphorus (P%), and potassium (K%) levels were observed in T8 (soil + BAC + FE), T7 (soil + biochar + compost + FE), and T6 (soil + biochar + FE), with values reaching approximately 3.9% N, 0.30% P, and 3.3% K, respectively—representing increases of up to 95% for N, 200% for P, and 75% for K compared to the control (T1: soil only, 2.0% N, 0.10% P, 1.8% K) treatment (Figure 12 and 13). These elevated macronutrient contents in the tissue align with enhanced nutrient availability and the nutrient-retention properties of charged/inoculated biochar and BAC, which can reduce nutrient leaching and improve cation exchange. Biochar alone (T2) and compost alone (T3) produced moderate improvements, while combinations (charging and inoculation) consistently outperformed single amendments. Along with the enhanced nutrient availability, the charged/inoculated biochar started out with more nutrients to begin with which also explains the increased macronutrient content in the tissue. While studies have shown that biochar over multiple years will have the most impactful benefits on nutrient cycling and availability (Bekchanova et al. 2024), this study suggests that charging and inoculating at time of application is best to see improved results quicker. The results from Agegnehu, et al (2015) study found that tissue nutrient content in peanut crop increase significantly under biochar-compost application compared to biochar only.

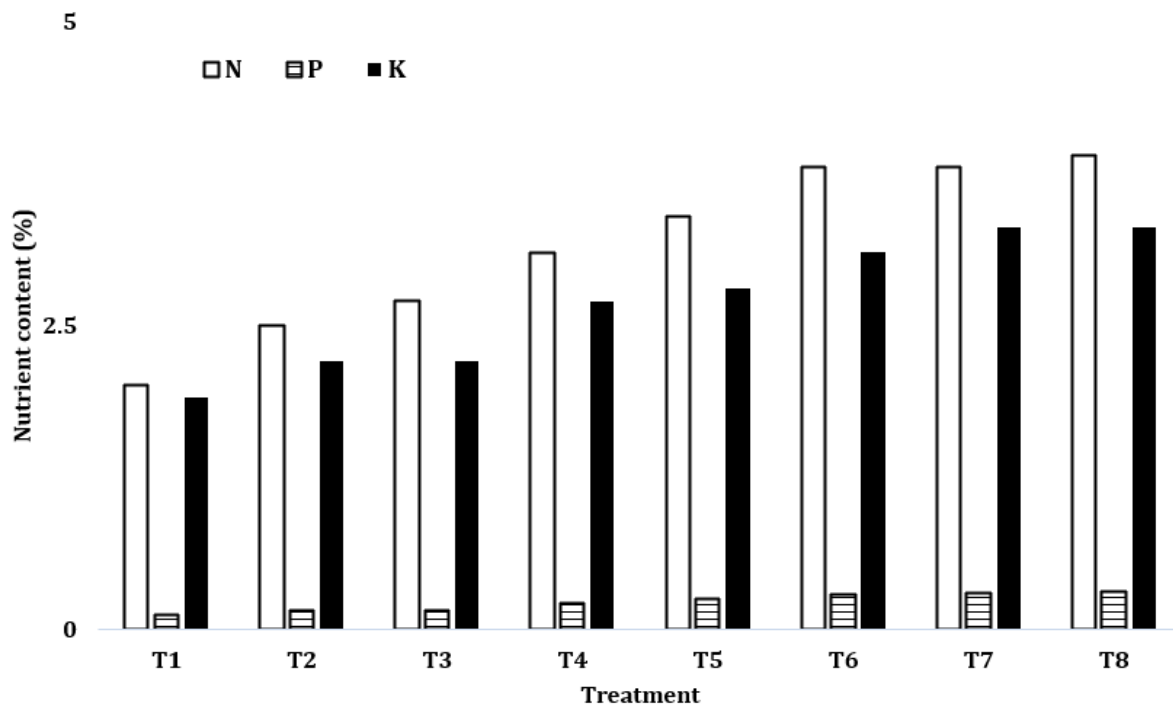


Figure (12) Nitrogen (N), phosphorus (P) and potassium (K) content (%) in pak choi tissue under the 8 treatments regardless of soil type.

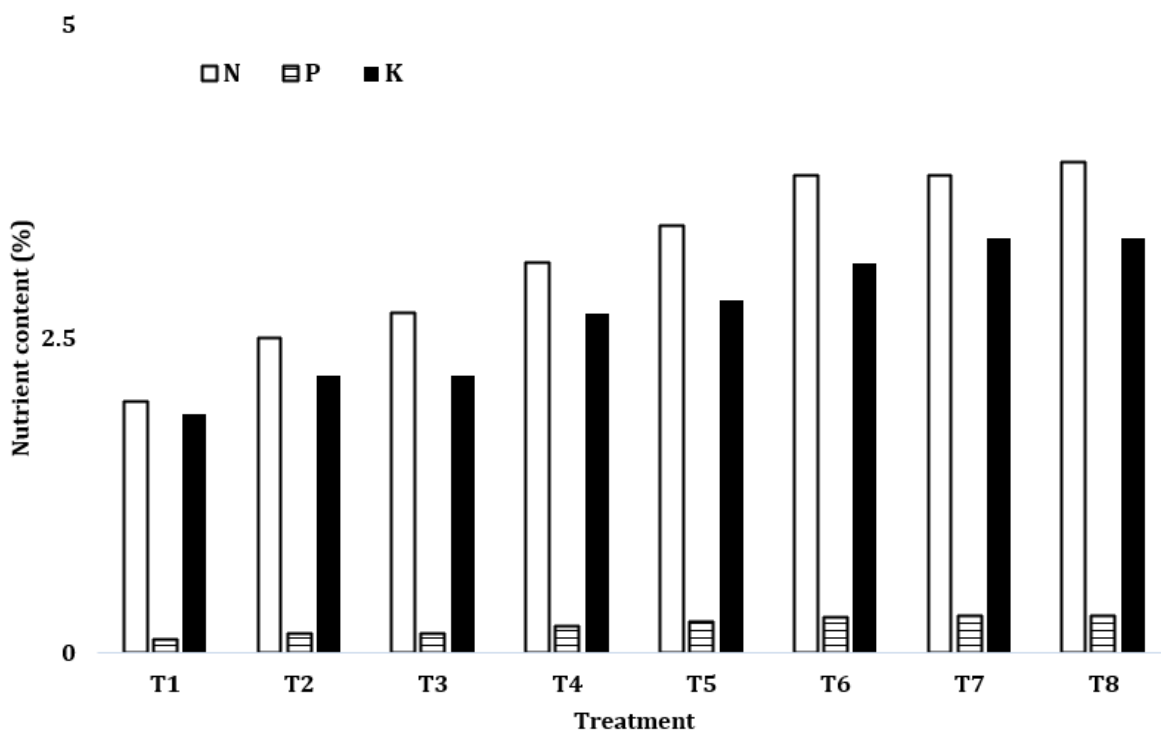


Figure (13) Nitrogen (N), phosphorus (P) and potassium (K) content (%) in beetroot tissue under the 8 treatments regardless of soil type.

Soil Health:

Elevated soil pH (45% increase under Oxisol and 20% increase under Mollisol) and CO₂ respiration rate (75% increase under both soils) in both soil types occurred for the charged/inoculated biochar and BAC, compared to soil and biochar only, indicating improved soil health. Soil CO₂ respiration rates, which measures for microbial activity and organic matter decomposition, were highest in T8, T7, and T6, and similar high-amendment treatments (3.2–3.3 g/m²), compared to the control (1.8 g/m²) (Figure 14), reflecting increased growth of microbes and, in effect, microbial respiration and enhanced biological activity. These findings are consistent with prior research showing that biochar, especially when charged or combined with compost and nutrient-rich liquids like fish emulsion, enhances microbial biomass and nutrient availability, while also improving soil health parameters. The increased nutrient availability and organic matter that is present in the charged/inoculated biochar treatments also helps provide suitable conditions for these beneficial soil microorganisms to thrive and in turn improve soil health.

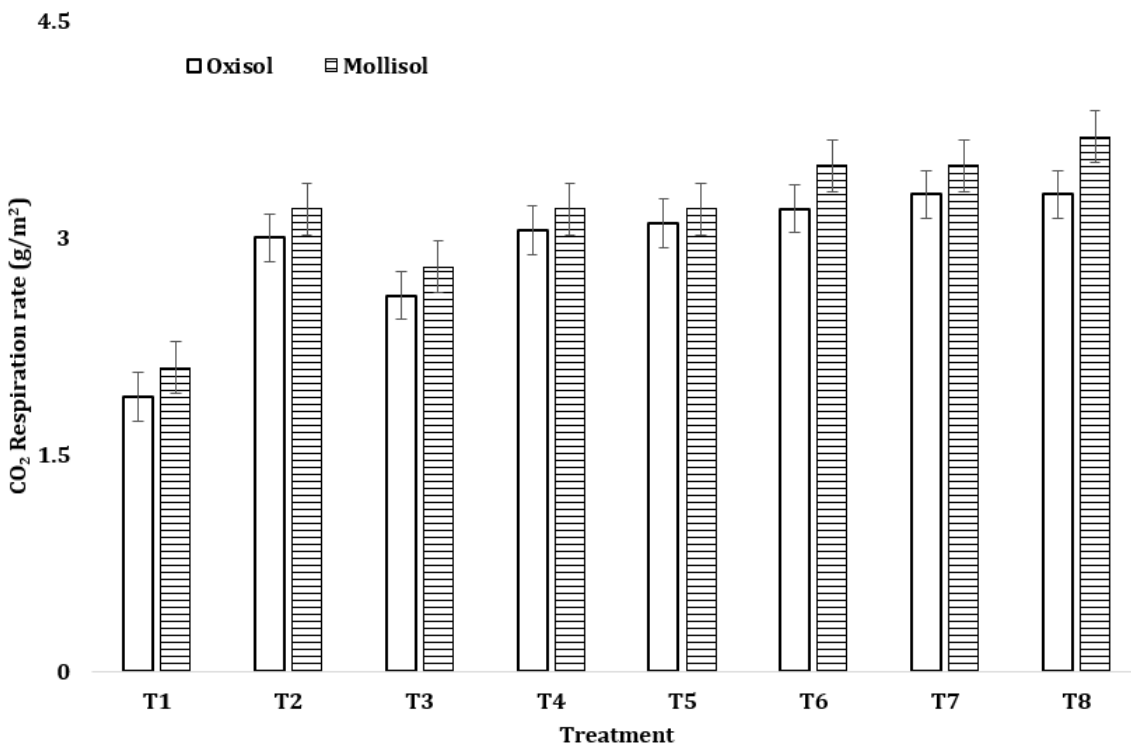


Figure (14) Soil CO₂ respiration rate (g/m²) under Oxisol and Mollisol soils regardless of crop.

Soil pH followed a similar pattern as the CO₂ respiration rate, with the highest values (6.7–6.8) in the most complex treatments (T8, T7, and T6) and the lowest (5.0) in the control (Figure 15), indicating that organic amendments—particularly those incorporating compost, BAC, and biochar—buffered acidity and raised pH toward the optimal range for beetroot growth (6.0–7.0). This pH shift likely contributed to improved nutrient uptake (Berek, 2015). With this improved nutrient uptake, we noticed that tissue

nutrient content in beets showed a clear gradient increase across treatments. With the pH increased to a suitable range for beetroot, it allowed for not just increased macronutrient uptake but also suggests that there was an increase in micronutrient uptake, overall healthier plants due to optimal soil pH, and reduced possibility for any nutrient toxicity. This increase in soil pH is expected as it has been found that biochar, in addition to BAC, can cause that increase (Tomczyk et al., 2020). While these amendments can act as a pH buffer, the initial soil properties do play a role in how much the pH will be impacted, as a more acidic soil such as the Oxisol used in this study will have a bigger increase in pH compared to a more neutral soil such as the Mollisol used. The results are in agreement with Agegnehu, et al (2015) which they found that biochar-compost application improved soil properties compared to biochar only under peanut crop. Also, Antonangelo, et al (2021) have reported in their review that soil properties and health under the application of biochar-compost combination improved compared to biochar only or control (soil only). Rawat, (2019) reported improved soil health parameters under biochar application.

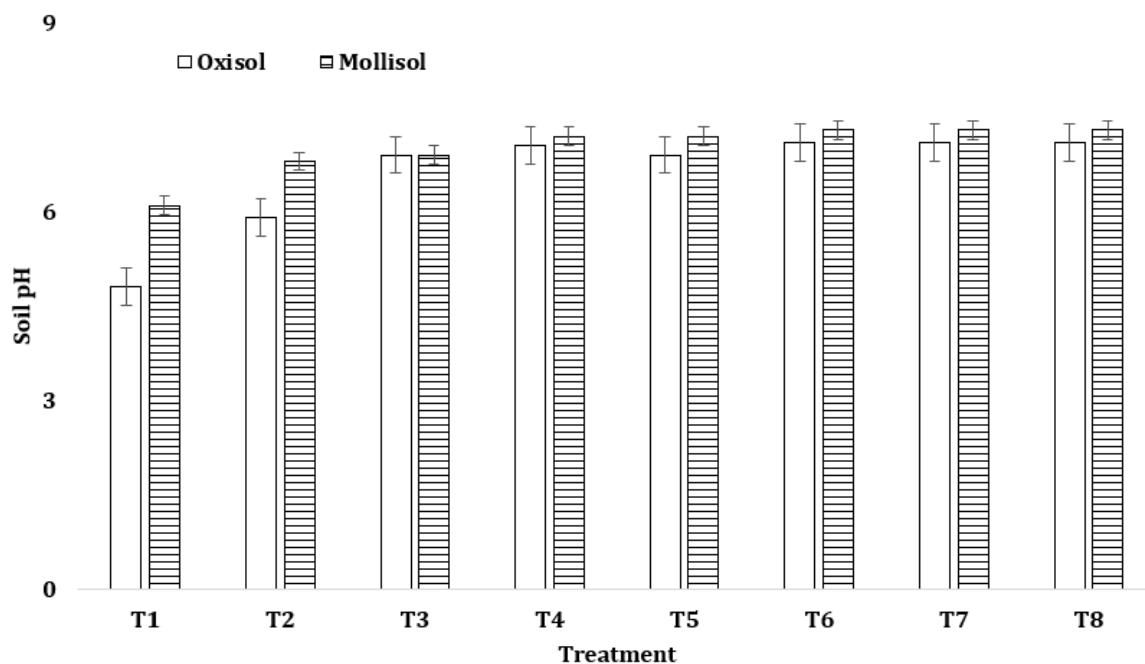


Figure (15) Soil pH under Oxisol and Mollisol soils regardless of crop.

Conclusions

Overall, the results demonstrate that integrating invasive species-derived biochar with organic amendments offers a strategy to increase crop nutrient and improve soil health, with the greatest benefits observed in treatments combining biochar charging and inoculation together. Along with sampling two different soil types, it was reflected that the biochar with organic amendment was beneficial to both of them. In addition to that, the results confirmed that charging/inoculating the biochar prior to applying it to soils is

beneficial to soil properties and crops growth and yield. While this study is limited in condition as a pot trial, it is possible for future studies to investigate the impact of the 8 different treatments in a field plot setup to include soil profile depth/equilibrium effect/interaction.

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IMPACTS OF NITROGEN RATES AND ENHANCED EFFICIENCY PRODUCTS ON KANSAS COTTON

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ABSTRACT

The purpose of this experiment was to determine the effect that different nitrogen fertilizer rates and additives have on cotton. Response parameters included seed cotton yield and gin turnout (lint percentage), as well as fiber quality factors such as length, uniformity, micronaire, strength, and color. Nitrogen management is crucial for Kansas cotton, given its indeterminate growth and relatively short growing season. Conducting nitrogen fertilizer studies across environments to develop region-specific and effective nutrient management practices in Kansas for cotton production is beneficial for optimizing nitrogen management for irrigated and dryland scenarios. A baseline of nitrogen response was assessed using five N rates, including a control, using urea broadcast at planting. The range of N rates was established based on historical yields and typical N response in the region and for the production system. A set of enhanced efficiency plant nutrition products (EEPNTs) was added at one N rate, targeting suboptimal rates, at one location. These included urease inhibitors, nitrification inhibitors, slow-release N fertilizer, and improved (streamed) placement. Treatments were replicated four times at each location and applied at pinhead square, the developmental stage where N uptake begins increasing significantly. Over three site years, two of which were irrigated and one of which was rainfed, none showed a statistically significant response to any tested level of nitrogen application. Additionally, of the four EEPNTs evaluated, there were no statistically relevant differences. Statistical meaningfulness was calculated based on whether the p-value was less than 0.05. Weed pressure, harvest timing, harvest conditions, and soil NO₃-N are some of the factors that could have limited response in the trials. Future research will utilize sites with lower soil NO₃-N and assess a wider range of N rates. Different cropping rotations that integrate cotton will also be studied to identify how nitrogen management differs across cropping systems (corn-cotton vs. soybean-cotton vs. sorghum-cotton, etc.).

PRECIPITATION IMPACTS ON REDISUDAL NITROGEN AND FERTILIZER-N EFFECTS ON DRYLAND CROP PRODUCTION

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ABSTRACT

Understanding how precipitation affects residual soil nitrogen (N) is essential for improving crop productivity and N use efficiency in dryland system. Accordingly, our objective was to evaluate how residual soil N and in season N fertilizer applications affected corn and soybean productivity under contrasting precipitation patterns. The current results quantified the effects of residual soil N and in-season N applications on grain yield, crude protein, and soil N balance in corn (*Zea mays L.*) and soybean (*Glycine max L.*) during the 2024 and 2025 growing seasons.

N application did not significantly affect corn or soybean grain yield in either year because of drought and higher soil residual N. Crude protein in corn was also not significantly influenced by N rate in 2024 or 2025. Soybean crude protein responded to N treatments in 2024, with the normal N application (0 lbs/ac) producing higher crude protein than the enhanced rate (60 lbs/ac), but no significant differences were observed in 2025. Enhanced N applications (120 lbs/ac in corn; 60 lbs/ac in soybean) led to a surplus of soil N after the dry 2024 season, largely due to reduced crop uptake under limited precipitation. Despite this N surplus, soil N balance did not significantly influence 2025 yields. However, a negative correlation between soil N balance and corn yield was revealed, suggesting a reduced crop response to additional fertilizer-N when residual N is high. There was no relationship between residual soil N and soybeans grain yield in 2025. Findings from the study supports soil sampling and adjusting fertilizer-N rates based on residual N in dryland corn production systems where productivity is dependent on in-season precipitation and available soil water.

INTRODUCTION

While management practices influence crop performance, precipitation ultimately governs productivity in dryland cropping systems. In the semi-arid Great Plains, precipitation is a primary concern for producers and often dictates which management practices to implement on the operation. Since yield is the ultimate driver of success, recent precipitation variability has contributed to more fluctuations in dryland crop yields (Obour et al., 2015). The timing of rainfall and distribution are also critical for dryland crop production. Water stress during grain fill reduces yield more severely than stress that occurs earlier in the growing season (Dietzel et al., 2016). Understanding how management practices, such as N applications, can buffer crops against precipitation variability is essential for improving productivity in dryland systems.

The addition of N to a cropping system can improve overall crop productivity, but the fate of that N applied depends on precipitation and plant available water at planting.

Under typical growing conditions, crops can remove roughly 50-60% of applied N, leaving a portion in the soil that can support the following crops (Sainju, 2017). However, N uptake is strongly influenced by precipitation. In a study by Sainju et al. (2018), soil N levels were higher following a dry growing season because of reduced crop growth, which limited N uptake, resulting in greater residual N at the end of the growing season. This surplus N becomes vulnerable to losses through volatilization, denitrification, leaching, or runoff. However, in water-limited systems, most of the N could remain in the soil and become available for the next crop reducing the amount of N required for the next crop. Therefore, evaluating soil N balance can help producers make management decisions that minimize N accumulation, reduce environmental losses, and improve the cropping system efficiency.

This study aimed to identify how residual soil N and in-season N fertilizer applications affected crop productivity in corn and soybeans under contrasting precipitation patterns observed in 2024 and 2025 growing seasons.

MATERIALS AND METHODS

Experimental Design

This study was initiated in 2024 at the Kansas State University Harold and Olympia Lonsinger Sustainability Farm in Osborne County, Kansas. Treatments consisted of complete factorial combination of tillage practices (NT and CT), cover crops (with and without) and crop rotations (corn, corn-soybean, and wheat-corn-soybean) and N fertility management (normal and enhanced N) for a total of 48 treatment combinations. Treatments were arranged in a randomized complete block design with three replications totaling 144 experimental units. Each individual plot was 80 ft long by 40 feet wide.

Grain Crop Management and Collection

Corn and soybeans were planted at the beginning of June, while winter wheat was planted in November. Corn and soybeans were both harvested in early November, while winter wheat was harvested in July. Grain yields were determined by collecting a single 5 ft x 80 ft pass Massey Ferguson 8XP plot combine. All soybean and wheat grain yields were adjusted to 13.5% moisture, and corn was adjusted to 15.5% moisture.

Grain samples were ground through a Wiley Mill and analyzed for N concentrations using a UNICUBE CN Analyzer (Elementar Americas, Inc., Ronkonkoma, NY). All N concentrations were converted to crude protein content by multiplying the N concentration by 6.25.

Soil Sampling

In May 2024, initial soil sampling for nutrients was collected using a hand soil probe from 0-5 cm and 5-15 cm soil depths. In January 2025, soil samples were collected using a Giddings probe from 0-30 cm and 30-60 cm. Each sampling was sent to the soil testing lab separately for nutrient analyses. Soil residual N amounts were calculated by combining total nitrate (NO_3^-) and ammonium (NH_4^+) levels from each sampling time and depth.

Nitrogen Balance

Nitrogen (N) balance was calculated using the following equation from Sainju, (2017):

$$\text{Nitrogen balance} = N \text{ inputs} - N \text{ outputs} - \text{changes in soil total N}$$

The N inputs for this research included a broadcasted urea fertilizer at two different application rates, normal and enhanced. In corn, the normal N rate was 60 lbs/ac and the enhanced N rate was an additional 60 lbs of N per acre to the normal rate, which was 120 lbs of N per acre for both corn and wheat. In soybeans, producers normally do not apply any N during the growing season. Therefore, the enhanced N application for soybeans would be 60 lbs of N per acre.

The N outputs were determined by how much N was removed from the 2024 harvest using the grain yield and N concentration from the grain.

$$N \text{ outputs} = \text{grain yield} \left(\frac{\text{lbs}}{\text{ac}} \right) \times N \text{ concentration (\%)}$$

The changes in soil total N was determined by subtracting the 2025 N content in a 0-60 cm profile from the initial soil analysis in a 0-15 cm profile in 2024.

$$\text{Change in Total Soil N} = 2025 \text{ Total Soil N (0 - 60cm)} - 2024 \text{ Total Soil N (0 - 15cm)}$$

Seasonal Precipitation Collection

Precipitation data was collected using the Kansas Mesonet system located in Osborne County, Kansas, which is about 20 miles southeast of the research site. Data was collected from March 1 – November 30 for both 2024 and 2025 growing seasons. The normal precipitation amount was based on the “Normal Annual Precipitation” map generated in 2020 by the Kansas State Climatologist's Office.

Statistical Analyses

All statistical analyses were completed using SAS version 9.4 (SAS Institute, 2012, Cary, NC). PROC GLIMMEX was used to analyze grain yields and crude protein content. N treatments were considered to be fixed effects, while replication was considered to be a random effect. PROC MIXED was used to analyze the N balance data, using N treatments as the fixed effect and replication as the random effect. PROC REG was used to determine if the N balance influenced 2025 grain yield. All analyses were considered significant at $P \leq 0.1$.

RESULTS AND DISCUSSION

2024 and 2025 Grain Yields

Grain yield differed between 2024 and 2025 was mainly due to precipitation received during the growing seasons (**Figure 1a and 1b**). The summer portion of the growing season received about one inch more rainfall in 2025 than in 2024. The biggest differences occurred in August through September, when precipitation in 2025 was 6 inches more than in 2024. Rainfall during this part of the growing season helps support grain fill and ultimately affects yield the most. In comparison to the current Normal precipitation (1991-2020), 2024 was 8 inches below normal while 2025 was only 1 inch below normal. N treatment effects on corn yields were not significant in either 2024 ($P = 0.54$) or 2025 ($P = 0.47$). Similarly, soybean yields in 2024 ($P = 0.11$) and 2025 ($P = 0.26$) were not different (**Figure 1a**).

2024 and 2025 Grain Crude Protein Content

Precipitation had little effect on grain protein content compared to grain yield (**Figure 2a**). Corn crude protein increased from 2024 to 2025, reaching 9.3% in both N treatments, a 0.8% increase from 2024. N rate did not significantly affect protein in either year (2024 Corn ($P = 0.6809$); 2025 Corn ($P = 0.77$)). In soybeans, crude protein increased by 2.0 - 3.0% from 2024-2025. N rate significantly affected soybean protein in 2024 ($P = 0.004$) but not in 2025 ($P = 0.14$).

Nitrogen Balance in soil after 2024 Harvest

Plots that received the enhanced N application (120 lbs N/ac in corn and 60 lbs N/ac in soybean) had a higher soil N balance after the 2024 harvest, indicating a significant treatment effect on residual N levels (Corn $P = 0.001$; Soybean $P = <0.000$) (**Figure 2b**). In 2024, corn yields and protein content were higher in enhanced N treatments due to the excess soil N within the soil. On the contrary, soybean yield and protein content was higher in normal N treatments in 2024. The N balance at the end of the season was negative, forcing the soybean to fix its own N due to low residual N at the beginning of the growing season and no additional N inputs. By the end of the growing season, normal N treatments in soybeans had a negative nutrient balance.

Nitrogen Balance Effect on 2025 Grain Yields

The first year of this study was not ideal due to drought conditions. Therefore, much of the N in the soil was not utilized and a portion remained in the soil for the following crop. This N balance in the soil did not have a significant effect overall on 2025 corn ($P = 0.72$) or soybean ($P = 0.63$) yields. However, regression analysis showed that in corn, there was a negative correlation between N balance and yield. Meaning that the more N present in the soil, the crops response to the N fertilizer will decrease, resulting in lower yields with higher N input (**Figure 3a**). In soybeans, there seems to be no correlation between N balance and yield (**Figure 3b**).

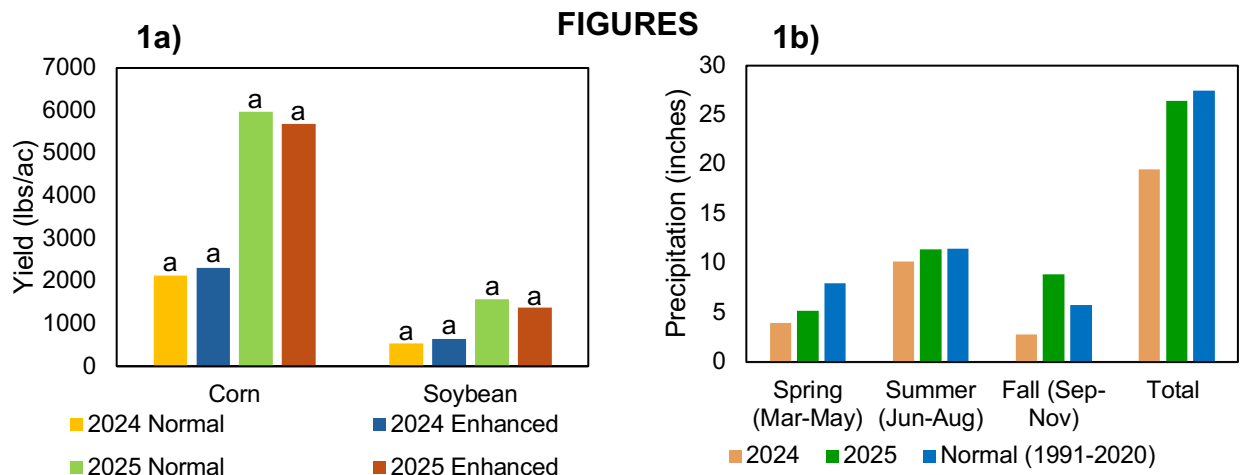


Figure 1: a) Enhanced N raised yields in 2024 and reduced them in 2025, though neither response was statistically significant. **b)** Cumulative precipitation by season and annual total for 2024 and 2025 compared with the 1991-2020 normal.

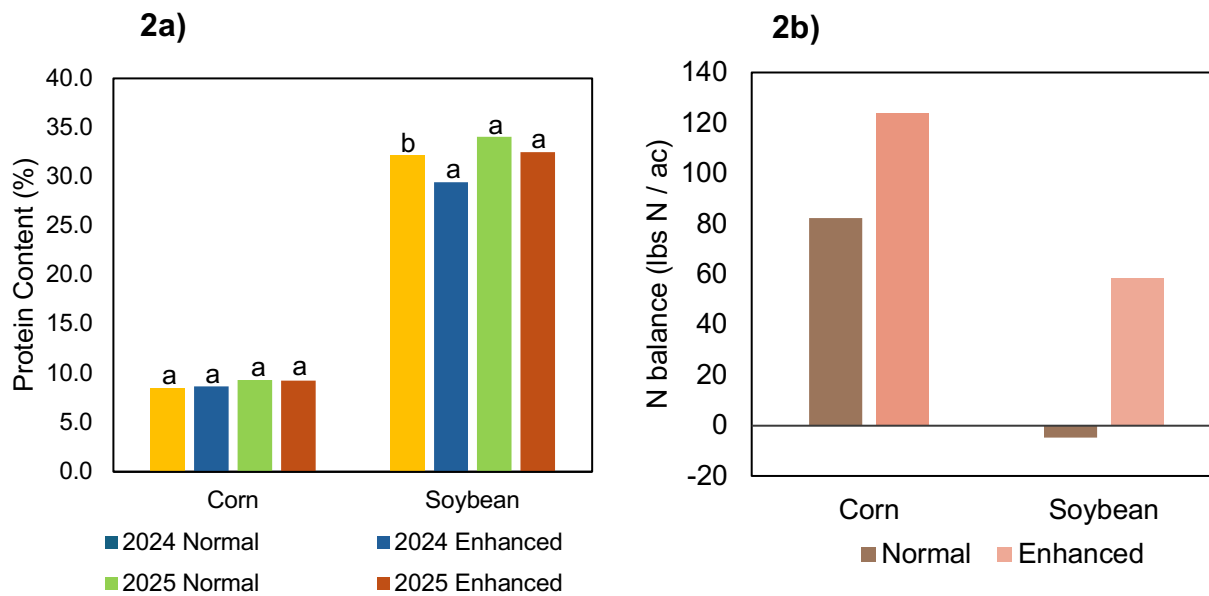


Figure 2: a) Corn protein was unaffected by N treatments either year, but soybean protein declined under enhanced N both years. **b)** N balance (lbs N per acre) for corn and soybean under Normal and Enhanced management. Positive values indicate a surplus of N left in the soil, and negative values indicate N loss after the 2024 growing season.

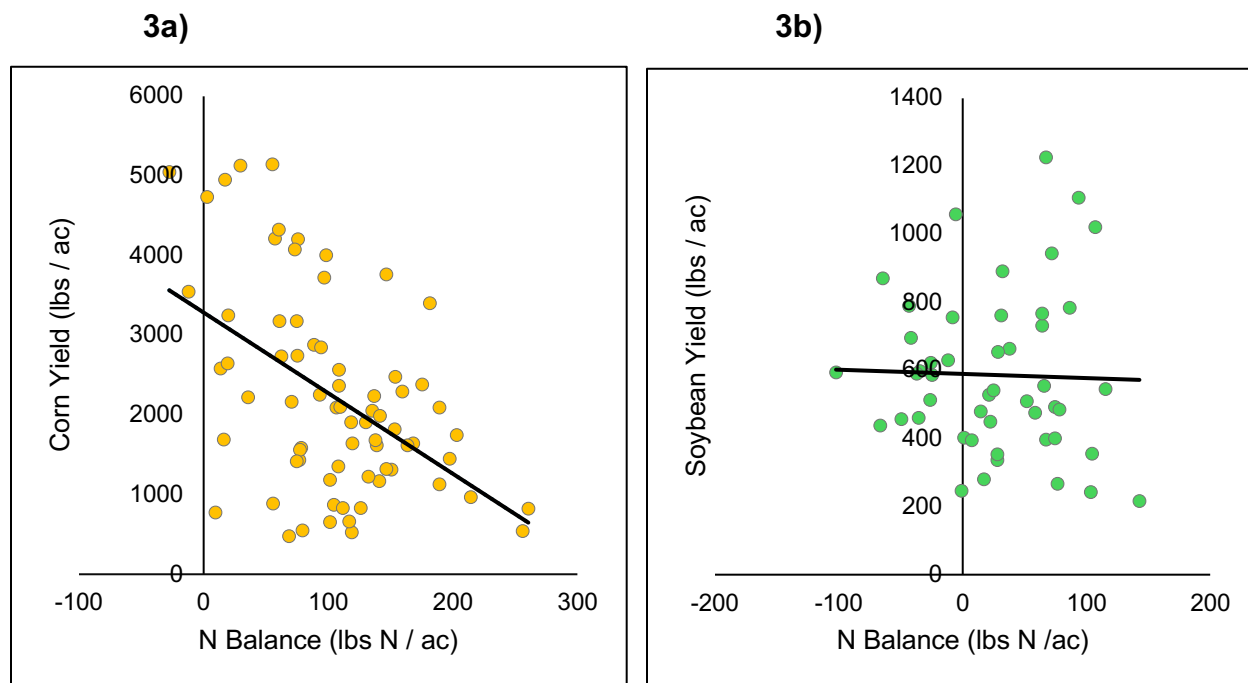


Figure 3: a) N balance did not significantly affect corn yield, but the negative correlation indicates reduced fertilizer responsiveness at higher residual N levels. **b)** Soybean yield showed no significant response to N balance, though a slight negative trend suggests lower yields at higher residual N levels.

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DIFFERENT SOURCES AND RATES OF NITROGEN FERTILIZERS INFLUENCE CARBON MINERALIZATION, NITROGEN CYCLING, AND SOIL pH OF TWO MAJOR SOIL SERIES OF TEXAS HIGH PLAINS

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ABSTRACT

Nitrogen is regarded as the most limiting factor in agricultural production because of its complex transformation, low uptake efficiency and multiple loss pathways. Excessive use of nitrogen fertilizers is practiced for agricultural production in Texas High Plains which impacts soil health in long run. With distinct soil types that run through the region, appropriate guide on fertilization is crucial, however, the information is still lacking. Hence, this study aims to investigate how different nitrogen sources and rates can impact carbon mineralization, nitrogen dynamics and pH of two soil series of Texas High Plains. A 140-days incubation trial was conducted at Texas A&M AgriLife Research at Lubbock center using two dominant soil series; Amarillo fine sandy loam from Lamesa and Acuff loam from Lubbock which were tested with three nitrogen fertilizers sources: urea ammonium nitrate (UAN), calcium nitrate (CN-9), and urea calcium ammonium nitrate (UCAN) at three rates: 50, 100, and 150 lb/acre including a control. Soil respiration was measured at 1d, 3d, 7d, 21d, 42d, 99 d, 102d, 117 d, and 140 d after fertilizer application, where nitrogen (nitrate and ammonium) dynamics, pH and EC were assessed at different sampling events as destructive sampling. Our findings suggest that nitrogen fertilizers can bring alkaline soil towards neutrality, but CN-9 can potentially cause soil salinization if applied at higher rate. UCAN showed higher soil respiration compared to other fertilizers sources if subsequent application of the fertilizer is practiced in both soil series. Nitrification was rapid with UCAN as compared to UAN but for immediate nitrate demand upon fertilizer application, CN-9 can be a better option. In general, UCAN at 100 lbs/acre can be recommended in nutrient management for producers of High Plains but site-specific field assessment is required for overall soil health and agricultural productivity.