

Cropping systems under water-limited conditions: effects of rotation and nitrogen management
on yield, resource use efficiency, profitability, and soil properties.

by

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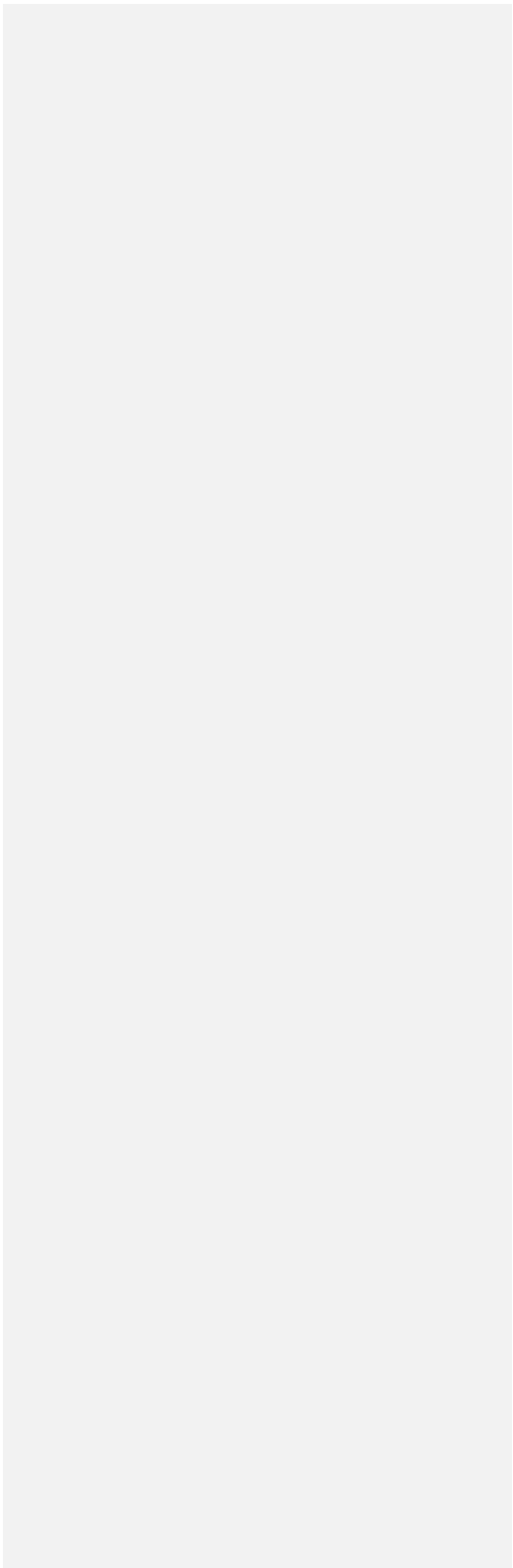
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Abstract

Sustaining agricultural productivity in water-limited regions such as the Central Great Plains requires cropping systems that balance yield, resource-use efficiency, and economic viability. This thesis integrates results from field studies conducted at different temporal scales, location and under different water-management conditions to evaluate how crop rotation diversity, cover crop integration, and nitrogen management strategies influence productivity, water-use efficiency (WUE), nitrogen-use efficiency (NUE), soil properties, and economic performance.

A long-term field experiment conducted from 2014 to 2024 under limited irrigation in south-central Nebraska evaluated five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W), using glucose equivalent yield (GE), WUE, NUE, and partial net return as integrative performance metrics. Continuous corn achieved the highest system-level productivity and partial net return but exhibited lower NUE due to higher nitrogen inputs. In contrast, C-Sb achieved the highest NUE but at the expense of productivity and WUE. Corn-wheat consistently underperformed across agronomic and economic indicators. C-Sg and C-C-W, provided balanced trade-offs among yield, efficiency, and profitability, highlighting how rotation design has trade-offs among productivity, resource-use efficiency, and short-term economic performance under limited irrigation. Soil responses to crop rotation were evaluated during Phase I (2015 to 2021): across rotations, total soil carbon and nitrogen stocks to 120 cm were not significantly altered, indicating that detectable changes in soil C and N pools may require longer observation periods. However, surface soil pH reflected cumulative nitrogen management history, with greater acidification in corn-intensive rotations. Mineral nitrogen patterns supported this interpretation,

while other soil chemical and physical properties showed limited rotation effects. Phase II (2022 to 2024) introduced a split-plot cover crop treatment to evaluate impacts on system productivity, WUE, and NUE. Despite two years of below normal rainfall, the inclusion of cover crops did not affect system productivity (expressed as glucose equivalent yield per hectare), WUE, or NUE in any rotation, demonstrating that cover crops can be integrated into limited irrigation systems without short-term performance penalties.

A complementary four year rainfed study in Kansas evaluated contrasting nitrogen management strategies in wheat. An integrated “progressive” 4R nitrogen approach (optimizing rate, timing, placement, and source) maintained grain yield while reducing nitrogen inputs and improving NUE compared with a conventional single application strategy. Soil moisture and in-season nitrate dynamics were not significantly affected.

Overall, this thesis demonstrates that no single management strategy optimizes all performance metrics. While continuous monoculture systems may maximize short-term returns, diversified crop rotations, cover crop integration, and improved nitrogen management offer more resilient pathways by enhancing resource use efficiency without sacrificing productivity. These findings support the adoption of integrated, systems-based approaches to improve the sustainability of cropping systems in the water limited environments of the Central Great Plains.

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Dedication

To my mother, who nurtured my curiosity and love of learning.

To my father, who taught me respect for the land and the meaning of hard work and persistence.

Chapter 1 - General Introduction and Thesis Organization

General Introduction

Agricultural production systems are under increasing pressure to adapt to a convergence of environmental, economic, and societal challenges, including climate change, water scarcity, soil degradation, and rising expectations for sustainability and resource efficiency (Foley et al., 2011; Tittonell, 2014; Hunter et al., 2017; Pretty et al., 2018). In water-limited regions, these pressures are particularly acute, as agricultural intensification must be achieved within increasingly constrained hydrological and nutrient budgets while maintaining economic viability. Addressing these challenges requires the development of resilient cropping systems that balance productivity with efficient use of water and nutrients, protect soil as a foundational resource, and remain adaptable to interannual climate variability (Lal, 2015).

In the U.S. Central Great Plains, crop production is closely linked to both limited precipitation and groundwater resources (Ogallala Aquifer). Declining aquifer levels, coupled with high evaporative demand and variable rainfall, have heightened concerns about the long-term sustainability of irrigated and dryland agriculture in the region (Gurdak et al., 2007; Scanlon et al., 2012; McGuire, 2014). Under these conditions, improving water use efficiency (WUE) and nitrogen use efficiency (NUE) has become central to sustaining crop productivity while reducing environmental risks such as nitrate losses, soil acidification, and declining soil quality. As a result, management practices such as crop rotation, cover crop integration, and nitrogen management have emerged as key levers for improving the performance of cropping systems in semi-arid environments. Crop rotation diversity is widely recognized as a cornerstone of resilient agroecosystems. Long-term studies have shown that diversified rotations can enhance yield stability, improve nutrient cycling, reduce pest and disease pressure, and increase both

water and nitrogen use efficiency relative to monoculture or low-diversity systems (Gaudin et al., 2015; Bowles et al., 2020; Renwick et al., 2021; Yusuf et al.). Rotations that incorporate crops with contrasting functional traits can influence soil structure, residue dynamics, and nutrient availability in ways that support more efficient resource use (Raimbault and Vyn, 1991). However, many existing studies are based on short-term experiments or do not reflect realistic water limitations, limiting their ability to capture cumulative effects, rotational legacy impacts, and trade-offs among productivity, efficiency, and profitability (Gurdak et al., 2007; Johnston and Poulton, 2018).

Cover crops have also gained attention as a complementary management practice for improving soil health, enhancing nitrogen retention, and increasing system resilience (Blanco-Canqui et al., 2015; Kaye and Quemada, 2017; Blanco-Canqui, 2018). Their effectiveness, however, is highly context dependent. In semi-arid and water-limited systems, concerns persist regarding potential competition for soil moisture and the risk of yield penalties, particularly in years with below-average precipitation. Integrated assessments that evaluate cover crops within diversified rotations and under limited irrigation remain scarce, especially those that simultaneously consider productivity, WUE, and NUE at the system scale.

Nitrogen management represents another critical dimension of cropping system sustainability, particularly in cereal-based systems. Nitrogen fertilization strongly influences yield, grain quality, and economic returns, yet inefficient nitrogen use contributes to environmental losses and increased production costs. Improving NUE requires strategies that better synchronize nitrogen supply with crop demand across variable soil and weather conditions. While substantial research has focused on individual nitrogen management practices

(such as fertilizer rate, timing, or source), fewer studies have evaluated integrated nitrogen strategies within diversified crop rotations.

This thesis addresses these knowledge gaps by evaluating cropping system performance across multiple spatial, temporal, and management dimensions in the Central Great Plains. Chapters 2 and 3 are based on a long-term (2014-2024) field experiment conducted under limited irrigation in south-central Nebraska designed to assess how diversity of corn-based rotations influences productivity, economic performance, water-use efficiency, nitrogen-use efficiency, and soil properties. Chapter 2 focuses on system-level productivity, resource-use efficiency, and partial economic returns across five contrasting corn-based rotations. Chapter 3 extends this analysis by examining soil responses to long-term rotation management and evaluating the short-term effects of cover crop integration on productivity, WUE, and NUE during a subsequent phase of the experiment.

Chapter 4 complements the limited-irrigation studies by shifting focus to rainfed wheat-based systems. Using a multi-year field experiment, this chapter evaluates how contrasting nitrogen management strategies interact with rotational diversity to influence wheat productivity and nitrogen use efficiency under dryland conditions. By comparing conventional and more adaptive nitrogen approaches within diversified wheat-based rotations, this chapter provides insight into how management decisions can improve NUE without compromising yield.

Together, the chapters of this thesis adopt a systems-based perspective to evaluate how crop rotations, cover crop integration, and nitrogen management influence productivity and resource use efficiency across irrigated and rainfed systems of the Central Great Plains. By integrating long-term field data with agronomic, soil, and efficiency metrics, this work

contributes to the development of more resilient and sustainable cropping systems capable of meeting the challenges of agriculture in water-limited regions.

Thesis Organization

This thesis is presented as a series of five chapters. Chapter 1 provides a general introduction and outlines the objectives and structure of the thesis. Chapter 2, “Ten Years of Corn-Based Crop Rotations under Limited Irrigation: Impacts on Yield, Nitrogen and Water Use Efficiency, and Profitability,” evaluates the long-term effects of rotation diversity on crop productivity, nitrogen and water use efficiency, and economic returns in a limited irrigation system. Chapter 3, “Long-Term Soil Changes and the Effects of Cover Crop Introduction on Yield, Nitrogen and Water Use Efficiency in Corn-Based Rotations under Limited Irrigation,” investigates changes in soil properties after seven years of rotation and examines the impact of introducing cover crops on yield and resource use efficiency. Chapter 4, “Effect of Crop Rotations and Nitrogen Fertilization Strategies on Productivity and Soil Quality,” presents results from a separate experiment conducted under rainfed conditions, assessing the influence of wheat-based rotations and nitrogen fertilization strategies on productivity, nitrogen use efficiency, profitability, and soil nutrients. Chapter 5 provides an overall synthesis and general conclusions derived from the findings presented in this thesis.

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Chapter 2 - Corn-Based Rotations under Limited Irrigation: Yield, Nitrogen, Water Use, and Profitability.

Abstract

Identifying crop rotations that maintain productivity while improving resource use efficiency is essential for the sustainability of agriculture in water-limited regions such as the Central Great Plains. The objective of this study was to compare different corn-based rotations in terms of productivity, water and nitrogen use efficiency, and economic return under limited irrigation. Five rotations were evaluated: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W), in a long-term field experiment (2014-2024) conducted in south-central Nebraska. Rotations were compared based on glucose-equivalent yield (GE, kg GE ha⁻¹), water use efficiency (WUE, kg GE mm⁻¹), nitrogen use efficiency (NUE, kg GE kg⁻¹ N), and partial net return (USD ha⁻¹). Continuous corn had the highest total productivity (13,575 kg GE ha⁻¹) and partial net return (USD 1,537 ha⁻¹), but lower NUE. In contrast, C-Sb achieved the highest NUE (102 kg GE kg⁻¹ N) with reduced productivity and WUE. C-W consistently underperformed across all indicators, showing the lowest NUE, WUE, and economic return. C-Sg and C-C-W showed balanced performance, with relatively high values across agronomic efficiency, and economic indicators. Rotational legacy effects were significant, with corn yields lowest when preceded by corn and highest when preceded by wheat or sorghum. No single rotation optimized all performance metrics; while continuous corn maximized short-term returns, diversified rotations such as C-Sg and C-C-W provided better trade-offs among yield, resource use efficiency, and economic performance, supporting long-term sustainability under limited irrigation.

Introduction

Agricultural systems are facing increasing pressure to adapt to complex evolving challenges, including climate change, resource scarcity, and new demands from markets and public policies. Future production systems are expected to respond to increasingly strict environmental requirements while meeting higher standards of quality, efficiency, and sustainability (Foley et al., 2011; Pretty et al., 2018). Among these challenges, water availability has become increasingly uncertain due to aquifer depletion and growing competition among sectors (Scanlon et al., 2012). At the same time, agricultural intensification must be reconciled with the protection of soil as a key ecological resource (Lal, 2015). Addressing these constraints requires the development of resilient, adaptive, and multifunctional production systems that contribute not only to yield and resource use efficiency but also to the environmental sustainability and economic viability of agricultural systems (Tittonell, 2014; Hunter et al., 2017).

The Ogallala Aquifer is a critical water source for U.S. agriculture, supplying more than one quarter of the groundwater used for irrigation in the nation (Gurdak et al., 2007; McGuire, 2014). However, water is being extracted from the aquifer at a much faster rate than it is recharged (McGuire, 2014), raising serious concerns about the long-term sustainability of irrigated agriculture across the Great Plains (Scanlon et al., 2012). In Nebraska, limited and variable rainfall combined with high evapotranspiration rates intensify the need for more efficient water use strategies to maintain crop productivity.

In this context, identifying crop rotations that maintain or improve yield while reducing water inputs is essential for enhancing agricultural resilience to drought and resource constraints. Long-term rotational diversity has been demonstrated to improve yield stability (Gaudin et al.,

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2015; Bowles et al., 2020; Renwick et al., 2021), enhance nitrogen and water use efficiency (Yusuf et al., 2009; Attia et al., 2015; Domuta, 2015; Hussain, 2019), reduce pest and disease pressure (Liebman and Dyck, 1993), and support nutrient cycling (Vanotti and Bundy, 1995; Gentry et al., 2001; Martin and Sprunger, 2021). Rotational cropping systems also contribute to improved soil structure and infiltration, leading to enhanced moisture retention and reduced runoff (Raimbault and Vyn, 1991; Zhou et al., 2020). However, much of the available research is limited to short-term trials, which often fail to capture cumulative effects, interannual variability, and performance under real-world irrigation constraints (Robertson et al., 2008; Gaudin et al., 2015; Johnston and Poulton, 2018).

To address this gap, a long-term field study was established at the Bayer Water Utilization Learning Center in Gothenburg, Nebraska, from 2014 to 2024. The experiment evaluated five corn-based crop rotations under limited supplemental irrigation: continuous corn, corn-sorghum, corn-soybean, corn-wheat, and corn-corn-wheat. The specific objectives of this study were to: 1) Analyze and compare the productivity and profitability of five different corn-based crop rotations; and 2) Evaluate nitrogen and water use efficiency (NUE and WUE) across these systems under limited irrigation.

This study seeks to provide insights into crop rotation strategies that optimize productivity and resource-use efficiency while supporting long-term sustainability in water-limited environments. The hypothesis was that diversified crop rotations would improve resource use efficiency while maintaining productivity under limited irrigation compared to continuous corn.

Material and Methods

Experimental site

From October 2014 to October 2024 a field experiment was conducted at the Bayer Water Utilization Learning Center (40.881571, -100.166506) located in Gothenburg, Dawson County, in South-Central Nebraska. The annual precipitation average for the location was 565 mm and the temperature 10.8 °C (Figure 2.1). The soil in the site location was classified as Wymore series, fine mesic Aquertic Argiudoll (Baillie, 2001), with a predominantly silty loam texture.

Experimental design and treatments

The field experiment was established as a randomized complete block design with three replications. The study included five treatments, each representing a distinct crop rotation. All rotations were managed so that each phase of the rotation was present every year, ensuring consistent comparison across time and treatment (Figure 2.2).

The crop rotations were managed under a strip-tillage system for corn, soybeans, and sorghum from 2014 to 2021 (except for 2019 which was no-till), transitioning to a no-tillage system after 2021. Wheat was under a no-tillage system from the beginning (Appendix A). The plots received limited irrigation from 2015 to 2018 and transitioned to rainfed conditions since 2019, except for 2021 which was again irrigated (Table 2.1). The plots were irrigated using a subsurface drip irrigation (SDI) system, a water-efficient method that delivers water directly to the root zone through buried drip lines beneath the soil surface (Lamm and Trooien, 2003).

Precipitation information from 2014 to 2017 and temperature for all the period was obtained from the Nebraska Mesonet station in Gothenburg (Shulski et al., 2018), while the information from 2018 to 2024 was obtained from the Bayer Water Utilization Learning Center.

Fertilization practices were tailored to each crop and growing season, with variations in nutrients (N, P, S, and Zn), rates, and timing based primarily on crop type, expected yield potential, and seasonal conditions; a summary is presented in Table 2.2.

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Calculations

Grain yield: Harvesting was carried out using a commercial-grade combine harvester equipped with a calibrated yield monitor. Yield data were collected during harvest and processed to determine the average yield per plot.

Glucose equivalent yield (kg GE ha^{-1}): was calculated by multiplying crop yield by a crop-specific glucose factor, which reflects the amount of glucose required to synthesize one kilogram of grain. The factors used were: 1.46 for soybean, 1.39 for corn, 1.36 for sorghum, and 1.27 for wheat (De Vries et al., 1983).

Commented [KR3]: isn't wheat higher in protein than corn or sorghum?

Commented [PG4R3]: Yes, but the glucose equivalent factor reflects the biochemical cost of synthesizing grain, including carbohydrates, protein, and oil content, rather than protein concentration alone. And the % of oil and carbs in corn and sorghum is higher than in wheat.

$$GE \text{ yield } (\text{kg ha}^{-1}) = \text{Yield } (\text{kg ha}^{-1}) \times \text{Glucose factor}$$

Precipitation use efficiency (PUE): was calculated as the ratio of yield, expressed in kilograms of glucose equivalent per hectare, to total precipitation received, using the following formula:

$$WUE = \frac{\text{Yield } (\text{kg GE ha}^{-1})}{\text{Total Precipitation (mm)} + \text{Irrigation (mm)}}$$

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Nitrogen use efficiency (NUE): is a widely used indicator for evaluating the sustainability and efficiency of nitrogen management practices in cropping systems (Dobermann, 2007). It was calculated as the partial factor productivity of applied nutrient (amount of grain produced per

unit of nitrogen applied). In this study, it was estimated as the ratio between grain yield expressed in glucose equivalent (kg GE ha⁻¹) and the total nitrogen applied (kg N ha⁻¹) in each treatment. The formula used was:

$$NUE = \frac{Yield (kg GE ha^{-1})}{N applied (kg N ha^{-1})}$$

Partial Net Return: was estimated by calculating the difference between gross income and the combined costs of nitrogen fertilization and irrigation. All values were based on 10-year average prices (2015-2024) obtained from publicly available USDA and NRCS sources. Gross income was calculated as the product of grain yield (kg ha⁻¹) and the 10-year average market price of the respective grain crop (USD kg⁻¹), as reported by the USDA Economic Research Service (ERS) Feed Grains Yearbook Tables (2024a). Nitrogen fertilization cost was calculated by multiplying the total amount of nitrogen applied (kg N ha⁻¹; Table 2.2) by the average nitrogen price (USD kg⁻¹), reported in the ERS Fertilizer Use and Price database (2024b). Irrigation cost was calculated as the total amount of irrigation applied (mm; Table 2.1) multiplied by a fixed average cost per mm of water applied (USD mm⁻¹), derived from NRCS EQIP cost lists for Nebraska and Kansas (NRCS, 2020, 2024). Finally, partial net return was calculated as:

$$Partial Net Return (USD ha^{-1}) = Gross income - N Fertilization cost - Irrigation Cost$$

The economic analysis in this study focused on partial net return, which includes only the main variable costs that differ among treatments (nitrogen fertilization and irrigation costs). This approach is widely used in agronomic field research (CIMMYT, 1988; Mohammed et al., 2024; Tigner and Johanns, 2024) as it allows for an effective comparison of management practice treatments without introducing the variability and uncertainty associated with fixed or common production costs.

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Statistical analysis

All statistical analyses were performed using R version 4.5.1 (R Core Team, 2025) within the RStudio integrated development environment (version 2025.9.1.401; Posit Team, 2025). Analysis of variance (ANOVA) was conducted to evaluate treatment effects on the response variables. Linear mixed-effects models were fitted using the `lmer` function from the `lme4` package, accounting for random effects such as replication and/or year depending on the experimental design. Model assumptions, including normality of residuals and homogeneity of variances, were assessed using diagnostic plots and functions from the `performance` and `car` packages. When significant treatment effects were detected ($p < 0.05$), estimated marginal means (EMMs) were obtained with the `emmeans` package, and multiple comparisons were performed using Tukey's Honestly Significant Difference (HSD) test. Significance groupings were visualized using compact letter displays.

Graphs and summary tables were primarily generated in R using `ggplot2`, `dplyr`, and `tidyr` packages. Additionally, selected plots (such as multivariate summaries, cumulative water supply and soil depth trends) were developed in Python version 3.13.1 (Python Software Foundation, 2024) using the `matplotlib`, `seaborn`, and `pandas` libraries to allow enhanced customization and integration with other data workflows. Final tables were exported to Excel using the `openxlsx` package.

Results and Discussion

Productivity

A linear mixed-effects model revealed a significant effect of rotation on GE yield ($\chi^2(4) = 25.5$, $p < 0.001$; Figure 2.3). Continuous corn produced the highest average yield (13,575 kg GE ha⁻¹), followed closely by corn-sorghum (12,199 kg GE ha⁻¹); these two treatments did not differ significantly. Both outperformed the corn-corn-wheat rotation (11,819 kg GE ha⁻¹), which showed intermediate productivity. In contrast, corn-wheat (9,777 kg GE ha⁻¹) and corn-soybean (9,576 kg GE ha⁻¹) had significantly lower yields, with corn-soybean being the least productive and statistically different from all other treatments.

The reduced productivity in rotations that included soybean or wheat is attributed to the inherently lower grain yield of these crops. However, the corn-corn-wheat rotation did not significantly differ from continuous corn or corn-sorghum, likely due to the yield advantage of corn when grown in rotation.

Despite the overall trend of higher glucose-equivalent productivity in continuous corn and corn-sorghum systems, the analysis of corn yields alone revealed significant differences across crop rotations ($\chi^2(4) = 22.3$, $p < 0.001$). Specifically, continuous corn had significantly lower corn yield compared to corn-corn-wheat (-1026 kg ha⁻¹, $p = 0.0023$) and corn-sorghum (-1077 kg ha⁻¹, $p = 0.0073$), as shown in Figure 2.4. This indicates that although continuous corn maximized system-level productivity when all crops were considered (via glucose equivalent), its corn yield component was outperformed in more diversified rotations.

These differences may be explained by agronomic benefits provided by wheat and sorghum within the rotation. Wheat allows for a longer summer fallow period prior to corn planting, enhancing soil water storage and reducing early-season water stress (Schlegel et al.,

2018, 2019). Both wheat and sorghum interrupt pest and disease cycles common in continuous corn systems and promote improved soil structure and microbial diversity through contrasting root systems (McDaniel et al., 2014; Huynh, 2023; Ahumada, 2023). In addition, sorghum contributes to weed suppression through allelopathic effects (Dayan et al., 2009; Farooq, 2020). Collectively, these mechanisms likely contributed to the increased corn yield observed in diversified rotations.

These findings align with long-term evidence that two-crop rotations can outperform continuous corn, particularly when the additional crop is wheat or sorghum. Under limited irrigation in western Kansas, continuous corn yielded $\approx 20\%$ less than rotations alternating corn with wheat or sorghum (Schlegel et al., 2016). In the present experiment, rotations including wheat (C-W, C-C-W) and sorghum (C-Sg) produced higher corn yields than continuous corn, whereas the corn-soybean rotation did not differ significantly from continuous corn and was lower than the wheat- and sorghum-based rotations (Fig. 2.4). One possible explanation is that, under limited irrigation, soybeans may have depleted more soil water prior to the subsequent corn crop than wheat or sorghum (Kanemasu et al., 1976). Wheat is harvested earlier and sorghum generally has lower seasonal water use, which may have allowed greater soil water recharge before corn planting. This contrasts with studies where corn following soybean often out-yields continuous corn: e.g., 7.10 vs 5.83 Mg ha⁻¹ across sites (Wilhelm and Wortmann, 2004) and a $\sim 13\text{-}15\%$ advantage across 29 environments (Porter et al., 1997). Overall, the rotation yield advantage depends on the preceding crop and environment; under limited irrigation, benefits are larger when corn follows wheat or sorghum.

While Figure 2.4 illustrates average rotational effects, Figure 2.5 presents the annual corn yield trends over the 10-year period. Continuous corn showed greater interannual variability than

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rotations including wheat or sorghum, with a CV of 19.1%, compared with 16.5%, 17.7%, and 18.4% for C-C-W, C-W, and C-Sg, respectively. These patterns suggest that crop diversification not only increases mean productivity but also improves yield stability under variable environmental conditions, supporting previous findings on the resilience benefits of rotational diversity (Schlegel et al., 2016; Sindelar et al., 2016).

As shown in Figure 2.6, corn yield was lowest when corn followed corn ($9,820 \text{ kg ha}^{-1}$), consistent with the continuous-corn yield penalty driven by limited N availability, residue accumulation, and weather interactions (Gentry et al., 2013), which also translate into greater yield variability and economic risk relative to diversified rotations (Stanger et al., 2008). In contrast, corn following wheat achieved the highest yield ($11,065 \text{ kg ha}^{-1}$), then, in descending order, sorghum ($10,784 \text{ kg ha}^{-1}$) and soybean ($9,999 \text{ kg ha}^{-1}$), showing the strong influence of the preceding crop on productivity under limited irrigation. Although wheat is sometimes viewed as a challenging predecessor when corn is planted soon after harvest (due to the high C:N straw and associated N immobilization and cooler, high-residue seedbeds) those drawbacks diminish with a fallow interval that allows residue decomposition and soil-water recharge. Under such conditions, wheat as a preceding crop can be beneficial: multi-year studies in the central Great Plains show that conserving taller wheat stubble through the fallow improves stored water and raises subsequent corn yields relative to short stubble or continuous corn (Adeyemi et al., 2020).

Water use efficiency

Following the GE yield ranking, rotation-scale water use efficiency (WUE) was lower in C-W and C-Sb (17.7 and $16.8 \text{ kg GE mm}^{-1}$; Fig. 2.7). Because this WUE metric is dominated by yield, the lower productivity of these rotations results in lower efficiency, even though the wheat

sequence received less irrigation overall (Table 2). Continuous corn showed the highest rotation-scale WUE ($24.4 \text{ kg GE mm}^{-1}$) and did not differ from C-Sg or C-C-W. Considering the corn phase alone, however, continuous corn produced the lowest corn yield and likewise exhibited lower crop-level WUE; notably, corn following wheat can show a stronger water-yield response than corn following corn or sorghum (Schlegel et al., 2020). At the rotation scale, patterns align with western Kansas results: systems dominated by corn or including sorghum tend to have higher water productivity, whereas sequences that include wheat have lower rotation-scale WUE largely because wheat itself has lower water productivity (Schlegel et al., 2016). The comparable WUE of C-C-W here suggests that, under these conditions, two consecutive high-yielding corn years and efficient irrigation management offset the lower water productivity of wheat.

Water supply conditions had a strong effect on water use efficiency (WUE) across crop rotations (Figure 2.8). During years with above-average water supply (2015-2019 and 2021), WUE was significantly lower across all systems than in below-average years (2020, 2022-2024). Under these wetter conditions, continuous corn (C) achieved the highest WUE ($20.6 \text{ kg GE mm}^{-1}$), while corn-wheat (C-W) and corn-soybean (C-Sb) had the lowest values (14.6 and $14.4 \text{ kg GE mm}^{-1}$, respectively), with statistically significant differences compared to C. Corn-sorghum (C-Sg) and corn-corn-wheat (C-C-W) exhibited intermediate WUE values and did not differ statistically from C. This pattern aligns with yield responses observed in this study: under higher water supply, corn and sorghum increased yields more than wheat and soybean, widening the gap in glucose-equivalent output between rotations and leading to larger differences in WUE.

In contrast, during years with below-average water supply, WUE increased in all rotations (ranging from 20.3 to $30.0 \text{ kg GE mm}^{-1}$), and no statistically significant differences were detected among them. Nevertheless, numerical differences among rotations remained

evident, with continuous corn and corn-sorghum tending to show greater WUE values than corn-soybean and corn-wheat. Higher year-to-year variability within rotations, combined with the smaller sample size in this category (four years vs. six in the wetter group), likely reduced the statistical power to detect differences. Moreover, under drier conditions, all systems tended to operate closer to their physiological efficiency limits (Petrík et al., 2023), which may have limited the relative advantage of any single rotation.

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Overall, these results suggest that water supply modifies the relative influence of crop rotation on WUE. Under greater water availability, systems containing more corn or including sorghum maintained higher efficiencies, while those including wheat or soybean were less effective at converting water into productive biomass. Under more limited water supply, numerical differences among rotations remained, but these were less consistent and not statistically significant.

Nitrogen use efficiency

Nitrogen use efficiency (NUE), expressed as kilograms of glucose-equivalent yield per kilogram of nitrogen applied, varied significantly across crop rotations (Figure 2.9). The highest NUE was observed in the corn-soybean (C-Sb) system, averaging 101.8 kg GE kg⁻¹ N, significantly greater than all other rotations. This result is largely attributed to soybean's biological nitrogen fixation, which reduces the system's dependence on external N inputs while supporting subsequent crop productivity. The corn-sorghum (C-Sg) and continuous corn (C) rotations followed with intermediate NUE values of 82.4 and 75.7, respectively, while corn-corn-wheat (C-C-W) performed similarly to continuous corn. The lowest NUE was found in the corn-wheat (C-W) system (67.6 kg GE kg⁻¹ N), where both crops typically receive N fertilizer but

have lower average yields, particularly wheat when converted to glucose equivalents. These findings suggest that including soybeans in the rotation can substantially enhance system-level nitrogen use efficiency, whereas corn-wheat rotations may require more careful management to optimize N use under limited irrigation.

At the crop level, NUE for corn followed the same pattern as corn yield, with rotations that achieved higher corn yields (e.g., C-Sg and C-C-W) also attaining greater corn-specific NUE than continuous corn. This indicates that system-level advantages of soybean integration and yield benefits of diversified rotations are reflected not only in total productivity but also in improved nitrogen use efficiency within the corn phase.

The relationship between nitrogen use efficiency (NUE) and water use efficiency (WUE) across crop rotations is illustrated in Figure 2.10. The figure indicates that rotations differed in their efficiency profiles, but that no rotation consistently maximized both NUE and WUE. Corn-soybean (C-Sb) clustered at the highest NUE values, often exceeding $100 \text{ kg GE kg}^{-1} \text{ N}$, but generally had lower WUE, indicating efficient nitrogen use at the expense of water productivity. In contrast, continuous corn (C) showed some of the highest WUE values, but only moderate NUE, reflecting greater water productivity but higher nitrogen inputs. Corn-wheat (C-W) occupied the lower-left portion of the graph, indicating low performance for both metrics. Corn-sorghum (C-Sg) and corn-corn-wheat (C-C-W) tended to occupy intermediate positions, suggesting a more balanced trade-off between nitrogen and water use efficiency. Overall, the figure highlights that maximizing one efficiency metric does not necessarily improve the other, emphasizing the need to balance both resource-use efficiencies under limited irrigation.

Partial Net Return

Crop rotation significantly affected partial net return ($\chi^2(4) = 17.46$, $p = 0.0016$), as shown in Figure 2.11, reflecting the combined influence of yield performance, input costs, and market value. Continuous corn (C) achieved the highest average partial net return (USD 1,537 ha⁻¹), closely followed by corn-soybean (C-Sb) and corn-corn-wheat (C-C-W), all of which were statistically similar (group a). Corn-sorghum (C-Sg) did not differ significantly from these but tended toward lower returns (group ab). In contrast, corn-wheat (C-W) had the lowest net return (USD 1,195 ha⁻¹) and was the only rotation significantly different from the others (group b). These results indicate that, under limited irrigation, most diversified rotations can achieve profitability comparable to continuous corn. The main exception was the corn-wheat rotation, which consistently performed lower across agronomic, efficiency, and economic metrics, a pattern previously reported for similar systems in western Kansas (Stanger et al., 2008; Schlegel et al., 2016, 2020). Profitability outcomes were also highly sensitive to fluctuations in grain and fertilizer prices, which can amplify or reduce differences among rotations depending on market conditions (USDA Economic Research Service (ERS), 2025).

Comparative synthesis

A comparative synthesis of agronomic, efficiency, and economic indicators (Figure 2.12) reveals that no single rotation excels in all dimensions. Instead, each system presents trade-offs: continuous corn maximizes productivity and profit but has lower NUE; C-Sb optimizes NUE but underperforms in WUE; C-C-W and C-Sg achieve balanced profiles; and C-W consistently ranks lowest. These findings emphasize that rotation choice under limited irrigation should align with producer priorities, whether maximizing yield, profit, or resource use efficiency. For many

contexts, diversified rotations such as C-Sg or C-C-W may offer a more resilient and sustainable path forward, balancing productivity with long-term resource stewardship.

Conclusion

This ten-year evaluation of five corn-based rotations under limited irrigation demonstrated that crop sequence strongly influences system productivity, resource use efficiency, and economic performance. Continuous corn (C) achieved the highest glucose-equivalent yield, water use efficiency (WUE), and partial net return, but exhibited lower nitrogen use efficiency (NUE) compared to diversified systems. In contrast, the corn-soybean (C-Sb) rotation achieved the highest NUE through the inclusion of a legume phase yet consistently ranked lower in productivity and WUE. Corn-sorghum (C-Sg) and corn-corn-wheat (C-C-W) provided more balanced outcomes, sustaining high productivity and profitability while maintaining moderate efficiency. Corn-wheat (C-W) consistently underperformed across all indicators, confirming its limited suitability under restricted water supply.

Water availability further shaped system responses. WUE increased during drier years, reflecting greater efficiency in converting limited water into yield, whereas differences among rotations became more pronounced in wetter seasons, when corn- and sorghum-dominant systems outperformed those including wheat or soybean. These patterns highlight the importance of precipitation variability in determining rotation performance under limited irrigation.

Overall, these findings indicate that rotation selection under limited irrigation should be considered a strategic management decision rather than the pursuit of a universally superior system. Different rotations prioritize different outcomes, and producers may choose systems that best align with their operational goals, whether maximizing productivity and profitability or

improving water and nitrogen use efficiency. In environments where irrigation capacity is limited, precipitation is variable, and producers seek to balance productivity with long-term resource conservation, diversified rotations such as C-Sg or C-C-W may provide more balanced performance between productivity and resource use efficiency.

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Tables and Figures

Table 2.1 Annual and average irrigation amounts (mm) from 2015 to 2024 for each crop within five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W).

Crop	Rotation	Annual Irrigation										Average
		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	
		mm										
Corn	C	89	97	25	25	0	0	100	0	0	0	34
Corn	C - Sg	140	114	38	25	0	0	100	0	0	0	42
Corn	C - Sb	89	89	51	25	0	0	94	0	0	0	35
Corn	C - W	140	114	76	25	0	0	71	0	0	0	43
Corn	C - C - W	114	97	57	25	0	0	86	0	0	0	38
Sorghum	C - Sg	51	51	76	0	0	0	100	0	0	0	28
Soybean	C - Sb	89	89	51	25	0	0	94	0	0	0	35
Wheat	C - C - W	0	0	0	0	0	0	0	0	0	0	0
Wheat	C - W	0	0	13	0	0	0	0	0	0	0	1

Note: Irrigation applied using subsurface drip irrigation (SDI).

Table 2.2 Fertilizer application details by year and crop, including nutrient type and application parameters: placement method, timing, application rate (kg ha⁻¹), and date of application. Nutrients include nitrogen (N), phosphorus (P), sulfur (S), and zinc (Zn). “NA” indicates that the application date was not recorded.

Year	Crop	Time & Place		Rate				Date
				N	P ₂ O ₅	S	Zn	
				----- kg ha ⁻¹ -----				
2015 - 2020	Wheat	Side-dressing	Streamer bars	112	67.3	28.0		NA
2015 - 2020	Corn	Pre-planting	Streamer bars		67.3	28.0	0.56	NA
2015 - 2020	Corn	Side-dressing	Streamer bars	168				NA
2021	Wheat	Side-dressing	Streamer bars	101	44.8	22.4		12-Apr
2021	Corn, Soybean and Sorghum	Pre-planting	Streamer bars		56.0	23.3	0.23	26-Apr
2021	Corn and Sorghum	At planting	Streamer bars	112				7-May
2021	Corn	Side-dressing	Streamer bars	67				22-Jun
2022	Corn, wheat and Sorghum	Pre-planting	Streamer bars	112	44.8	18.5	0.18	12-Apr
2022	Corn and Sorghum	Side-dressing	y-drop	67				24-Jun
2022	Soybean	At planting	with planter	22	44.8	18.5	0.18	22-May
2023	Wheat	Side-dressing	Streamer bars	67				21-Apr
2023	Corn, Wheat, Sorghum, and Soybean	Side-dressing	Streamer bars	33	67.3	28.0		23-May
2023	Corn	Side-dressing	y-drop	168				23-Jun
2024	Corn and Sorghum	At planting	with planter	33	67.3	28.0	0.28	17-May
2024	Soybean	At planting	with planter	33	67.3	28.0	0.28	8-May
2024	Corn, Wheat, Sorghum, and Soybean	Side-dressing	Streamer bars	78				16-May
2024	Corn	Side-dressing	y-drop	168				19-Jun
2024	Sorghum	Side-dressing	y-drop	75				25-Jun

Note: Placement refers to the method of fertilizer delivery relative to the crop row: “streamer bars” (surface banding), “y-drop” (side application near plant base), and “with planter” (in-furrow or banded at seeding). Timing categories: “Pre-planting” (before seeding), “At planting” (during seeding operation), and “Side-dressing” (during early crop growth).

Table 2.3 Crop management practices, including tillage system, planting and harvest dates, and seeding densities ($\times 10^4$ seeds ha^{-1}), for the rotations evaluated in this study. The information reflects the typical management for each crop across different years and treatments.

Crop	Tillage	Planting Date	Harvest Date	Density $\times 10^4$ seeds ha^{-1}
Corn	No-Till	6 May - 6 Jun	18 Oct - 23 Oct	5.9 - 6.4
Corn	Strip-Till	7 - 26 May	20 Oct - 25 Oct	5.9 - 6.4
Sorghum	No-Till	4-8 Jun	9 Oct - 14 Nov	9.8 - 16
Sorghum	Strip-Till	26 -30 May	24 Oct - 24 Nov	9.8 - 16
Soybean	No-Till	11 May - 6 Jun	25 Sep - 24 Oct	34.6
Soybean	Strip-Till	8-31 May	28 Sep - 20 Oct	34.6
Wheat	No-Till	12 Oct - 19 Nov	11 Jul - 2 Aug	345.9

Note: Corn, soybean, and sorghum were under strip-tillage until 2021 (except 2019, which was no-till), and under no-tillage thereafter. Wheat was always no-till.

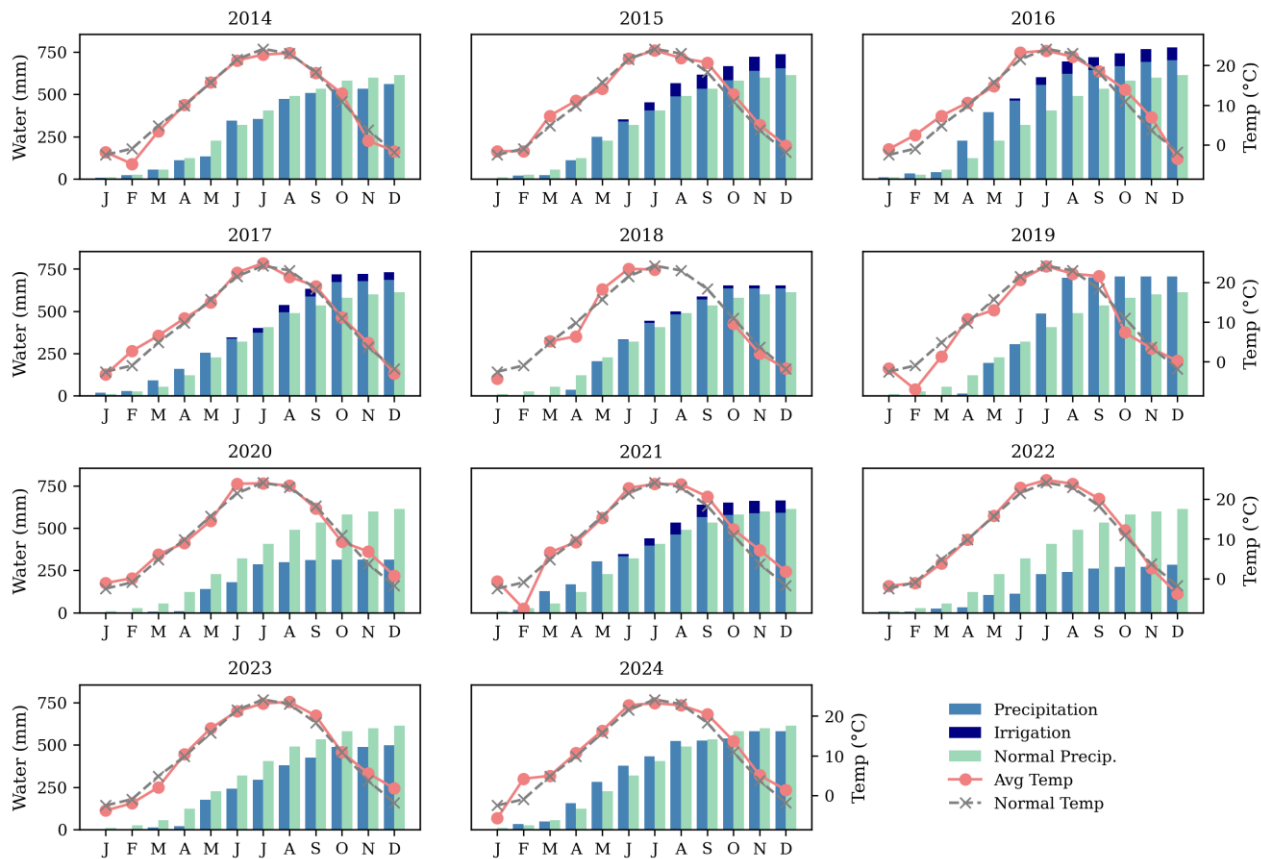


Figure 2.1 Accumulated monthly water supply (precipitation + irrigation, mm) and average monthly temperature from 2014 to 2024 at the Gothenburg Learning Center Station. Dark blue bars represent irrigation, light blue bars precipitation, and green bars the 1991-2020 monthly precipitation normal (NOAA, 1991). Red lines with circles represent average monthly temperature for each year, and gray dashed lines with crosses represent the 1991-2020 temperature normal.

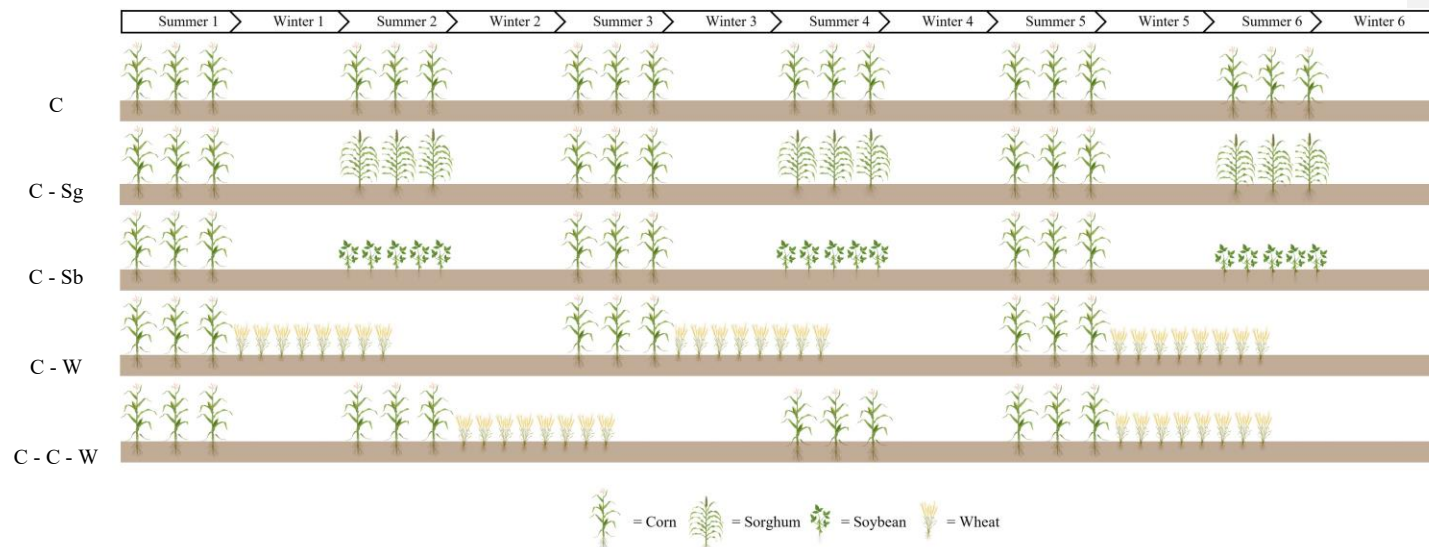


Figure 2.2 Conceptual diagram of the five crop rotations evaluated in this study under limited irrigation: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Each row represents one rotation, and icons depict the sequence of crops grown over the cycle (left to right). Cycles were repeated annually on the same plots from 2015 to 2024.

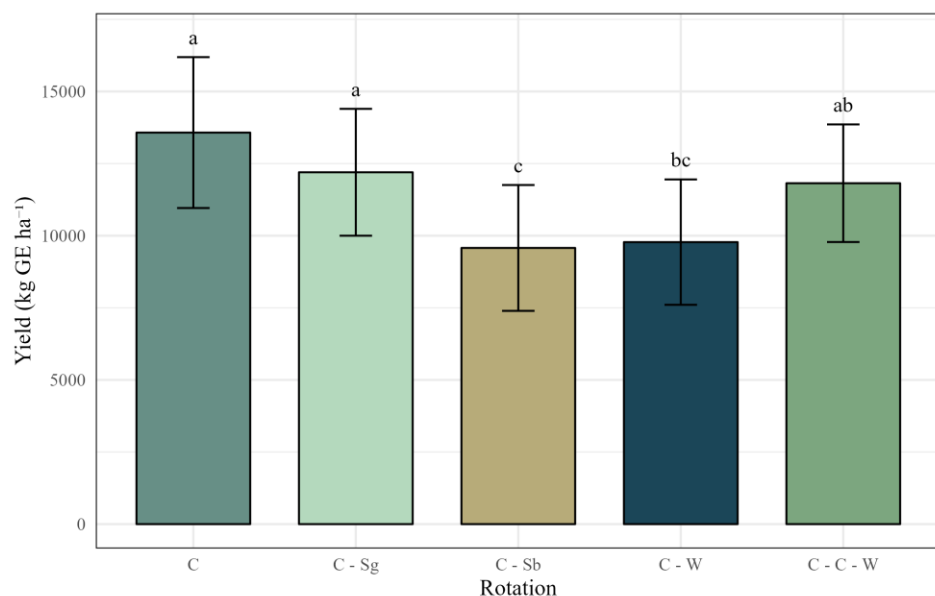


Figure 2.3 Mean annual productivity for each crop rotation, expressed as glucose equivalent yield (kg GE ha⁻¹) from 2015 to 2024, across five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Bars represent estimated marginal means from a linear mixed-effects model with year and replication included as random effects. Error bars indicate standard errors. Different letters above bars denote statistically significant differences between rotations based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$, Kenward-Roger method for degrees of freedom).

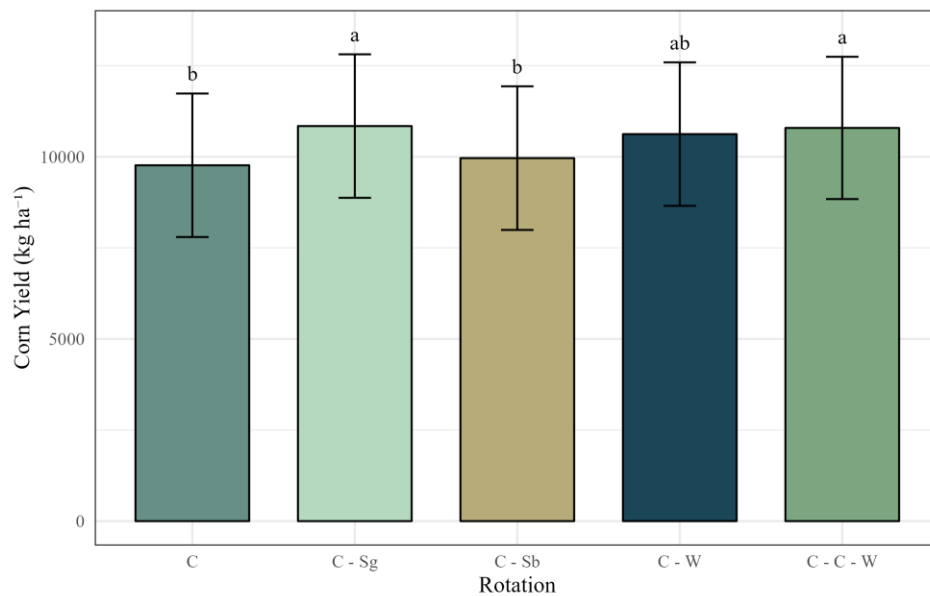


Figure 2.4 Average annual corn yield (kg ha^{-1}) from 2015 to 2024 across five crop rotations: C = continuous corn, C-Sg = corn-sorghum, C-Sb = corn-soybean, C-W = corn-wheat, and C-C-W = corn-corn-wheat. Bars represent estimated marginal means from a linear mixed-effects model with year as a random effect. Error bars indicate standard error. Different letters denote significant differences among rotations according to Tukey's honestly significant difference (HSD) test at $\alpha = 0.05$.

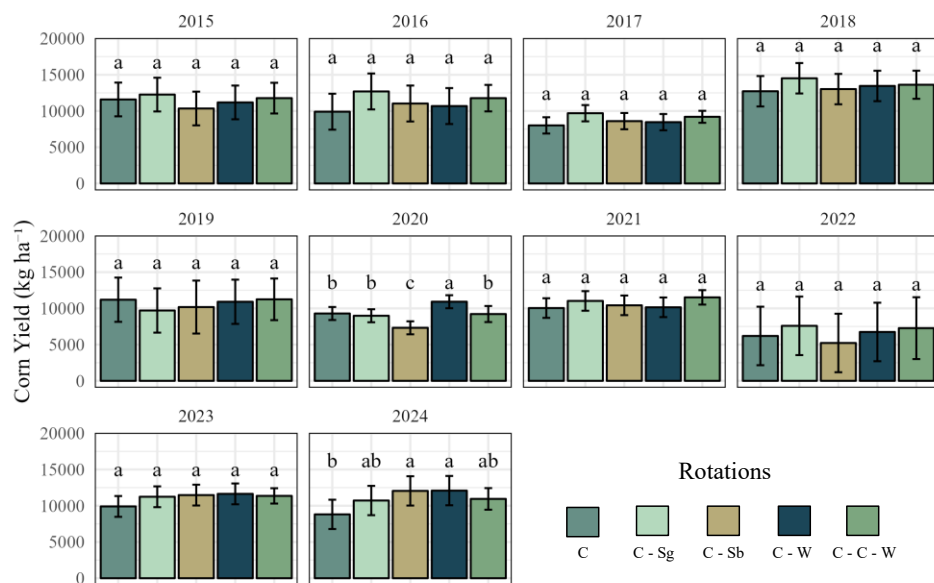


Figure 2.5 Annual corn yield (kg ha^{-1}) from 2015 to 2024 across five crop rotations: C = continuous corn, C-Sg = corn-sorghum, C-Sb = corn-soybean, C-W = corn-wheat, and C-C-W = corn-corn-wheat. Bars represent estimated marginal means from linear mixed-effects models fitted separately for each year. Error bars indicate standard error. Different letters within each year denote significant differences among rotations according to Tukey's honestly significant difference (HSD) test at $\alpha = 0.05$.

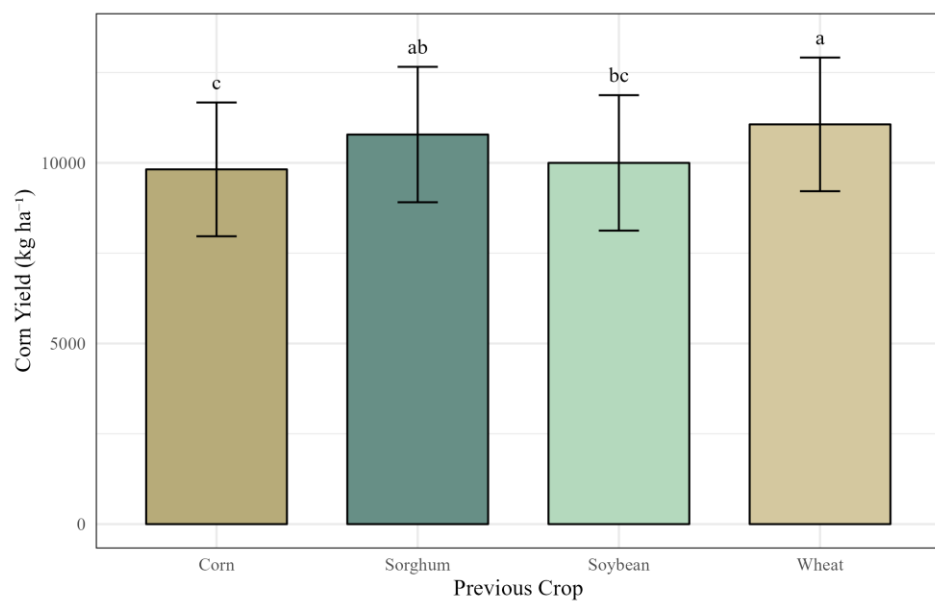


Figure 2.6 Mean corn grain yield (kg ha⁻¹) by preceding crop (corn, sorghum, soybean, and wheat) averaged over ten years (2015-2024) and five rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W), under limited irrigation. Error bars represent standard error. Different letters indicate significant differences among preceding crops based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$).

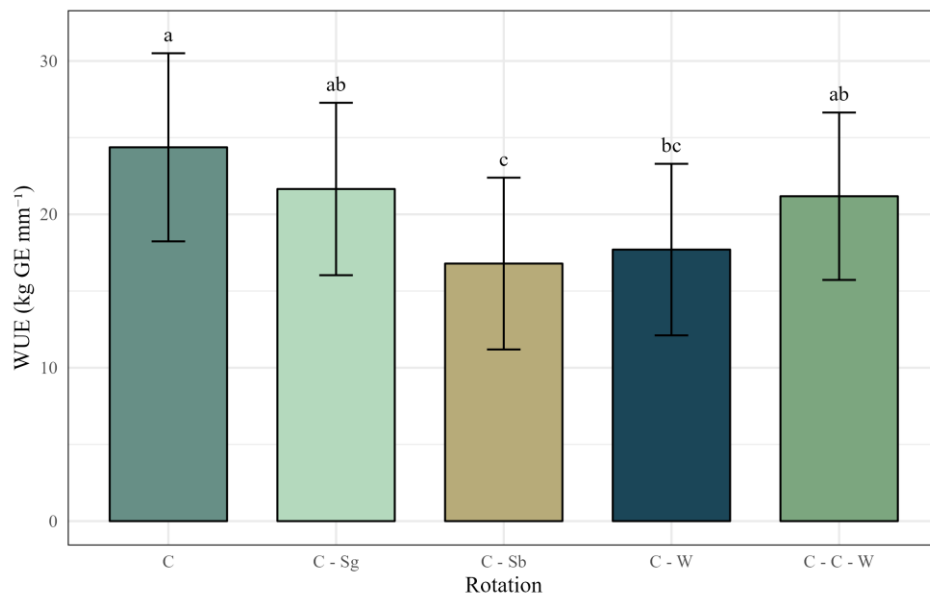


Figure 2.7 Average annual water use efficiency (WUE, kg GE mm⁻¹) from 2015 to 2024 for five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Bars represent estimated marginal means obtained from a linear mixed-effects model with year and replication as random effects. Error bars indicate standard errors. Different letters above the bars denote statistically significant differences between rotations based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$; Kenward-Roger method for degrees of freedom).

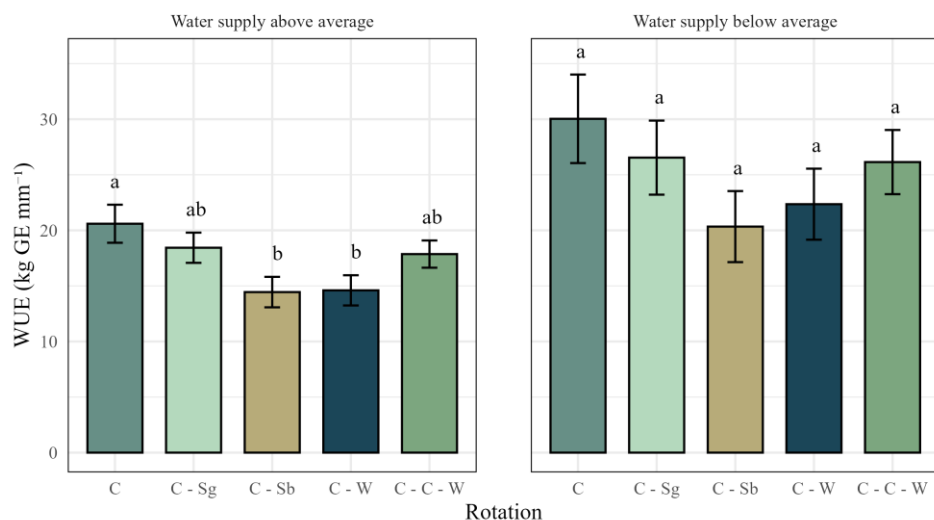


Figure 2.8 Average water use efficiency (WUE, kg GE mm⁻¹) across five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W), under contrasting water supply conditions: above the historic average (2020 and 2022-2024) and below the historic average (2015-2019 and 2021). Bars represent estimated marginal means obtained from a linear mixed-effects model with year and replication as random effects. Error bars indicate standard errors. Different letters above the bars denote statistically significant differences between rotations within each water supply category based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$; Kenward-Roger method for degrees of freedom).

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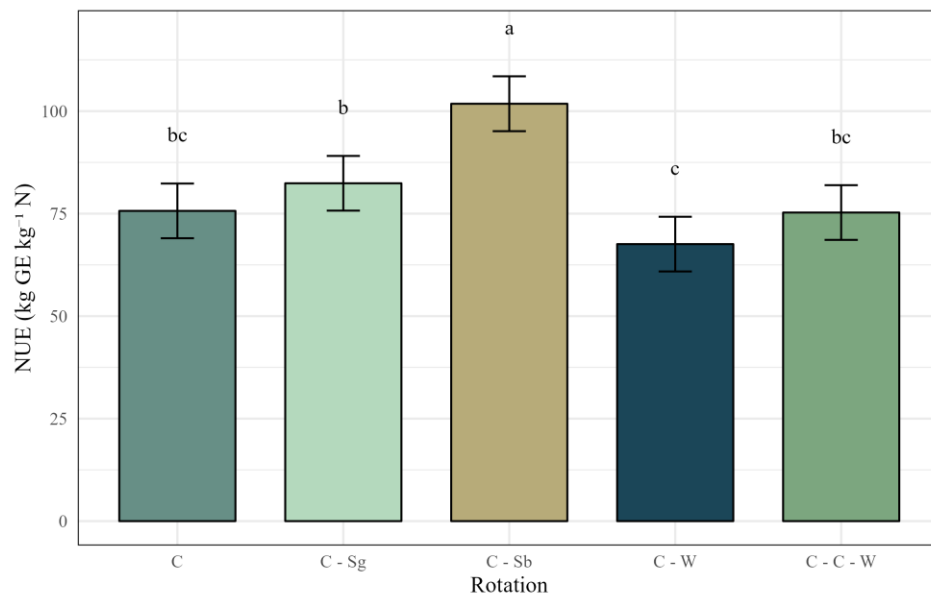


Figure 2.9 Average nitrogen use efficiency (NUE, kg GE kg⁻¹ N) from 2015 to 2024 across five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Bars represent estimated marginal means obtained from a linear mixed-effects model with year and replication as random effects. Error bars indicate standard errors. Different letters above the bars denote statistically significant differences between rotations based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$; Kenward-Roger method for degrees of freedom).

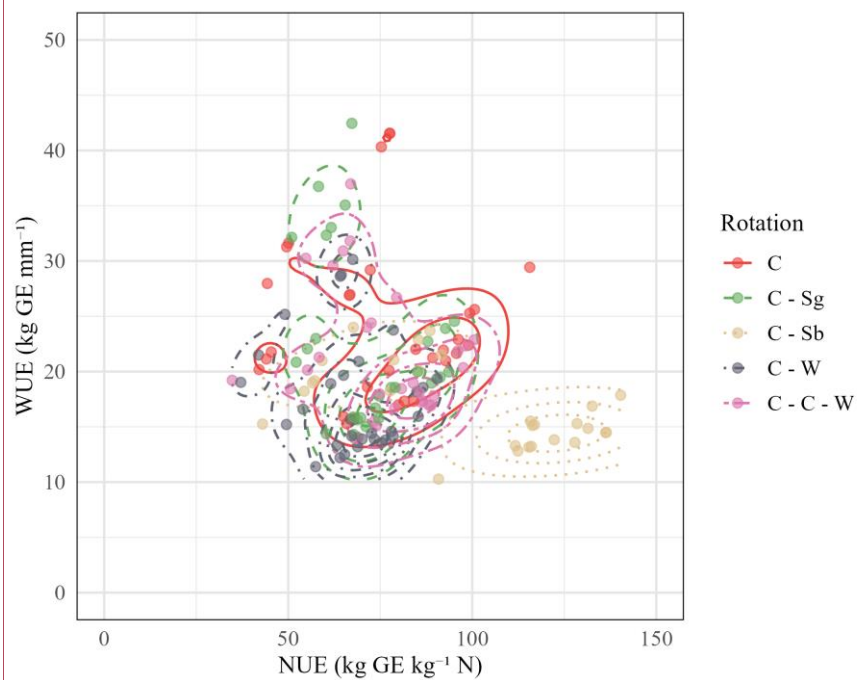


Figure 2.10 Relationship between nitrogen use efficiency (NUE, kg GE kg⁻¹ N) and water use efficiency (WUE, kg GE mm⁻¹ water) from 2015 to 2024 across five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Points represent annual values for each rotation, and contour lines indicate density estimates by rotation.

Commented [KR11]: What does this figure tell us?

Commented [PG12R11]: I revised the paragraph to clarify the main message of Figure 2.10, emphasizing that no rotation consistently maximized both NUE and WUE. I also clarified the distinct efficiency profiles among rotations and the trade-offs between nitrogen and water use efficiency under limited irrigation.

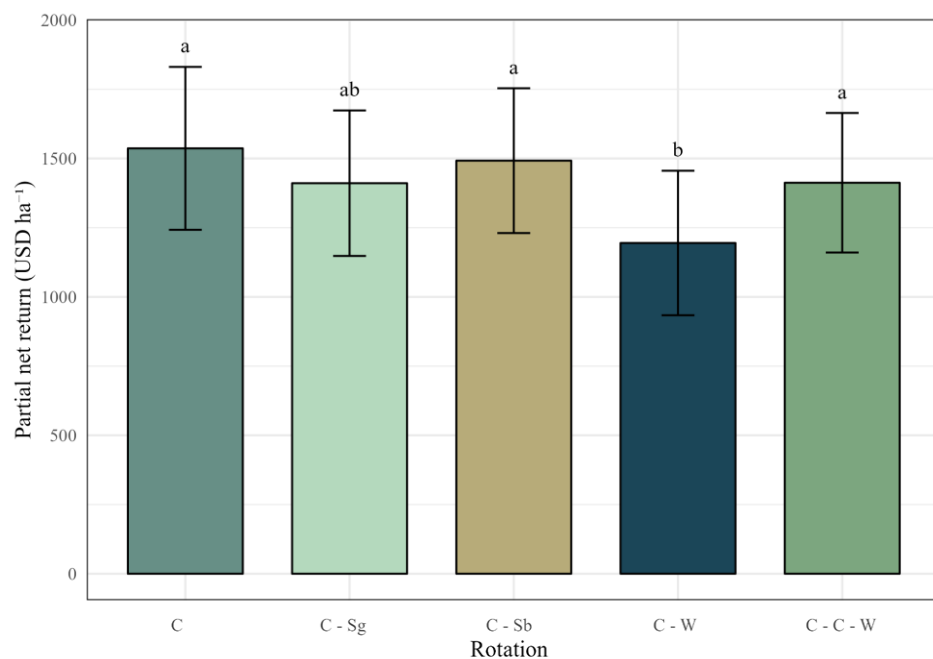


Figure 2.11 Average annual partial net return (USD ha⁻¹) from 2015 to 2024 across five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Bars represent estimated marginal means from a linear mixed-effects model with year and replication as random effects. Error bars indicate standard errors. Different letters above bars denote statistically significant differences between rotations based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$, Kenward-Roger method for degrees of freedom).

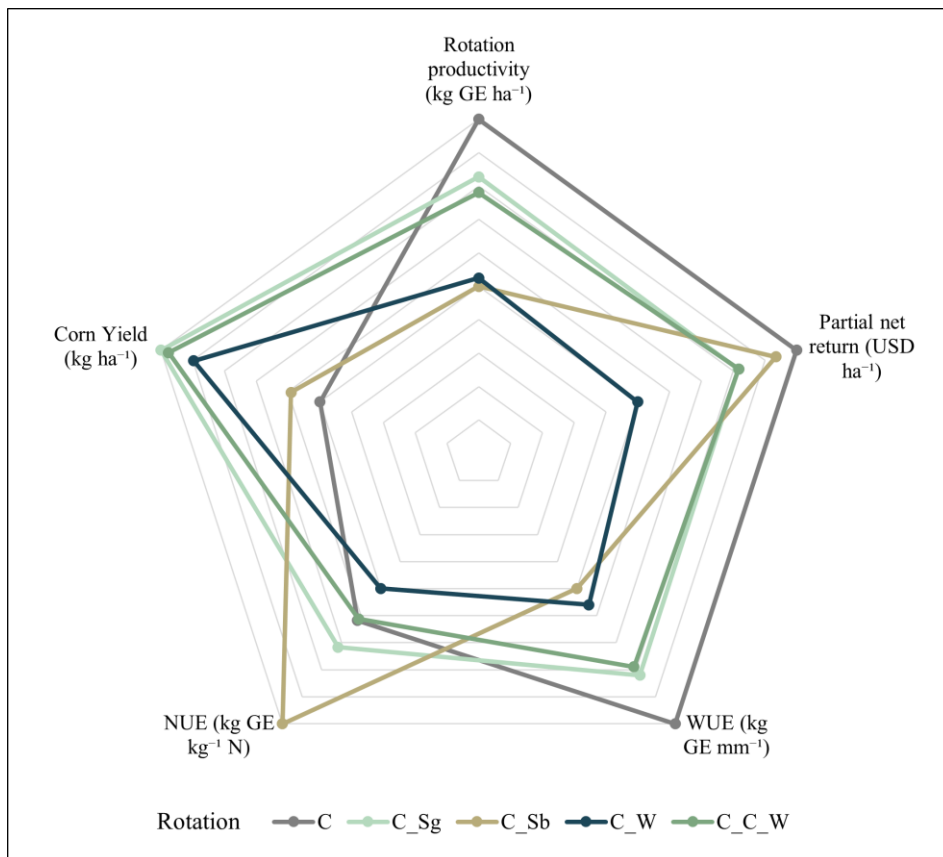


Figure 2.12 Comparison of five corn-based crop rotations (C = continuous corn, C-Sg = corn-sorghum, C-Sb = corn-soybean, C-W = corn-wheat, and C-C-W = corn-corn-wheat) based on five performance indicators: rotation productivity (kg GE ha⁻¹), corn yield (kg ha⁻¹), partial net return (USD ha⁻¹), water use efficiency (kg GE mm⁻¹, WUE), and nitrogen use efficiency (kg GE kg⁻¹ N, NUE). Values represent the 10-year average (2015-2024) for each indicator, expressed as estimated marginal means from linear mixed-effects models.

Chapter 3 - Long-Term Soil Changes and the Impact of Cover Crop

Introduction in Corn-Based Rotations under Limited Irrigation.

Abstract

Designing resilient cropping systems for water-limited regions requires evidence on how rotation diversity and cover crops affect soil properties, productivity, and resource use efficiency. The objective of this study was to assess changes in soil properties under different corn-based rotations, and evaluate the effects of cover crops on productivity, nitrogen use efficiency (NUE), and water use efficiency (WUE) under limited irrigation. A 10-year field experiment (2014-2024) was conducted in south-central Nebraska and structured in two phases. Phase I (2014-2021) evaluated soil responses to five rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Phase II (2022-2024) introduced a cover crop treatment within each rotation to assess effects on system performance. Rotation effects on total soil carbon and nitrogen stocks were not detectable across the 0–120 cm profile after seven years under the conditions of this study. Surface pH was lower in corn-dominated systems (C and C-C-W), consistent with greater ammoniacal-N inputs. Penetration resistance varied with depth but not with rotation. Despite two drier-than-normal rainfed years, cover crops did not reduce overall system performance: yield, WUE, and NUE were similar with and without cover crops across all rotations. Overall, rotation-driven changes in whole-profile soil C and N stocks were not detectable within the seven-year evaluation period (2014-2021), consistent with the slow turnover rates under semi-arid conditions, whereas surface acidification reflected N management history. Under timely termination, cover crops were integrated without short-term trade-offs in yield, WUE, or NUE.

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Introduction

Agricultural systems in semi-arid regions face the dual challenge of sustaining high productivity and preserving natural resources under limited water availability. In the U.S. Central and Great Plains, corn-based rotations dominate irrigated cropland, but reliance on long term monocultures or low diversity rotations can lead to soil degradation, reduced nutrient cycling, and declining yield stability (Wienhold et al., 2006; Sindelar et al., 2016; Bowles et al., 2020). These issues are magnified by climate variability and declining groundwater resources (Scanlon et al., 2012; McGuire, 2014), making it critical to identify management strategies that maintain soil health and resource use efficiency while supporting profitable crop production.

Diversified crop rotations and the inclusion of cover crops are increasingly recognized as management practices for improving soil health, nutrient cycling, and system resilience (Rosa et al., 2021; Inveninato Carmona et al., 2022). Rotations that integrate crops such as wheat, soybean, or sorghum can influence soil organic matter, nutrient dynamics, and water retention (Raimbault and Vyn, 1991; Vanotti and Bundy, 1995; Gentry et al., 2001; Yusuf et al., 2009; Attia et al., 2015; Martin and Sprunger, 2021); while cover crops have the potential to reduce erosion, improve water infiltration, and enhance nitrogen retention (Fageria et al., 2005; Blanco-Canqui et al., 2015; Blanco-Canqui, 2018). Furthermore, these practices can contribute to carbon sequestration and climate change mitigation (Kaye and Quemada, 2017; Schön et al., 2024). However, their outcomes are strongly influenced by environmental conditions, species composition, and management intensity.

Although numerous studies have examined cover crops and rotational diversity separately, there is limited long-term evidence on their combined effects in irrigated systems of the Great Plains. In particular, few have simultaneously assessed their influence on crop

productivity, nitrogen use efficiency (NUE), and water use efficiency (WUE) under limited irrigation. This lack of integrated research is especially relevant as producers seek to transition toward more sustainable management without sacrificing economic returns.

This study addresses this research gap through a 10-year field experiment (2014-2024) conducted in South-Central Nebraska under limited irrigation. The experiment was structured in two phases to evaluate complementary aspects of cropping system management. Phase I (2014-2021) focused on assessing changes in soil properties resulting from five contrasting corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). The hypothesis was that long-term corn-based rotations differing in crop diversity and intensity would lead to measurable differences in soil properties, with more diversified rotations improving indicators of soil quality relative to continuous corn

Phase II (2022-2024) introduced cover crops within each rotation to examine their influence on crop productivity, nitrogen use efficiency (NUE), and water use efficiency (WUE). By integrating long-term soil and crop data with resource use metrics, this study provides insights into designing resilient cropping systems that balance productivity with soil and water conservation in water-limited environments. This phase was based on the hypothesis that cover crops could enhance resource use efficiency while maintaining crop productivity across rotations.

Materials and Methods

Experimental site

From October 2014 to October 2024, a long-term field experiment was conducted at the Bayer Water Utilization Learning Center in Gothenburg, Nebraska (40.881571, -100.166506),

located in Dawson County in the south-central region of the state. The soil is classified as Wymore series, fine mesic Aquertic Argiudoll (Baillie, 2001), and the texture was predominantly silty loam, with a silty clay loam layer between 15 and 60 cm depth (Table 3.1).

During Phase I (2014-2021), the average annual precipitation was 606 mm and the mean temperature was 10.7 °C. In Phase II (2022-2024), average precipitation and temperature were 455 mm and 11.1 °C, respectively (Figure 3.1).

Experimental design and treatments

The experiment followed a randomized complete block design with three replications and was structured in two distinct phases:

Phase I: 2014-2021 - Crop Rotations and Soil Changes

From 2014 to 2021, each plot was managed as a full unit (whole plot), with five crop rotation treatments assigned randomly within each block: Continuous corn (C), Corn-sorghum (C-Sg), Corn-soybean (C-Sb), Corn-wheat (C-W), and Corn-corn-wheat (C-C-W) (Figure 3.2). All rotation phases were present each year, allowing for annual comparison across treatments.

Phase II: 2021-2024 - Introduction of Cover Crops

In 2021, each main plot was divided into two equal subplots to introduce a cover crop treatment: “With cover crops”, and “Without cover crops”. This created a split-plot structure, with rotation as the whole-plot factor and cover crop treatment as the subplot factor. The same subplot assignment was maintained from 2021 to 2024.

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Commented [PG15R14]: For the analyses performed in Chapter 2, data from all 10 years were included. Soil data analyses were based on 7 years, since soil sampling was conducted in 2021. Cover crop analyses included 3 years, from 2022 to 2024, because cover crops were introduced into the rotations in 2021.

Crop Management

Precipitation information from 2014 to 2017 and temperature for the entire period were obtained from the Nebraska Mesonet station in Gothenburg (Shulski et al., 2018). Precipitation data from 2018 to 2024, and irrigation records, were obtained from the Bayer Water Utilization Learning Center field management logs.

Limited supplemental irrigation was applied from 2015 to 2018 using a subsurface drip irrigation system and discontinued in 2019. Irrigation resumed only in 2021 (Table 3.2).

Applications were generally based on soil moisture data, crop growth stage, and expected precipitation, although some years received less irrigation because of operational limitations. Corn, soybean, and sorghum were managed under strip tillage until 2021, after which all plots transitioned to no-till, whereas wheat was managed under no-till throughout the study.

Fertilization practices were tailored to each crop and growing season, with variations in nutrients (N, P, S, and Zn), rates, and timing; a summary is presented in Table 3.3. Cover crops were selected and seeded after each main crop depending on crop rotation and planting window. A detailed summary of cover crop species, planting rates (kg ha^{-1}), preceding crop, and planting dates is provided in Table 3.4, and an overview of rotation phases and associated cover crop treatments is shown in Figure 3.2.

Field Measurements and Laboratory Analyses

In 2021, soil samples were collected to evaluate long-term changes in soil properties after seven years of rotational treatments. Two sampling methods were employed: i) Giddings probe: A hydraulic soil coring system equipped with a 5-cm diameter probe was used to collect two soil cores per plot. Cores were divided into six depth increments: 0-5, 5-15, 15-30, 30-60, 60-90, and

Commented [KR16]: More explanation of why irrigation was managed this way would be helpful.

90-120 cm. Cores from the same depth within each plot were composited, resulting in one sample per depth per plot. ii) Hand probe: A manual soil probe with a core diameter of 2.5 cm was used to collect samples at 0-5 and 5-15 cm depths. For the 0-5 cm layer, 24 subsamples were taken per plot and composited, while for the 5-15 cm layer, 12 subsamples were composited to obtain one representative sample per plot and depth. All soil samples were air-dried at 40 °C, ground, passed through a 2 mm sieve, and stored in plastic containers for subsequent analysis.

Soil analysis

Total carbon (C) and total nitrogen (N) were determined by dry combustion using an elemental analyzer, following the method described by Nelson and Sommers (1996). Soil organic matter (OM) was estimated by the loss on ignition (LOI) method, following the procedure described by Combs and Nathan (1998). Inorganic nitrogen (NO_3^- and NH_4^+) was extracted with 2 M KCl and analyzed following the method of Mulvaney (1996).

Soil pH was measured in a 1:1 soil-to-deionized water suspension following the method described by Watson and Brown (1998). Plant-available phosphorus (P) was extracted using the Mehlich-3 solution as described by Frank et al. (1998). Exchangeable potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) were extracted with 1 M ammonium acetate at pH 7.0 and analyzed using flame atomic absorption spectrometry, following the protocol of Warncke and Brown (1998). Cation exchange capacity (CEC) was determined using the ammonium displacement method described by Chapman and Pratt (1962). Soil texture was analyzed by the hydrometer method, as outlined by Gee and Bauder (1986).

Soil moisture

To determine soil moisture content using the gravimetric method (Briggs and McLane, 1910), a fresh soil sample was first weighed to obtain its wet weight. The sample was then dried in an oven at 105°C (221°F) for 24 hours. Then, the sample was weighed again to obtain its dry weight. The moisture content was then calculated as the difference between the wet and dry weights, expressed as a percentage of the dry weight:

$$\text{Moisture Content}(\%) = \frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Dry Weight}} \times 100$$

Soil Penetration Resistance

Soil compaction was measured using a FieldScout SC900 Soil Compaction Meter (Spectrum Technologies Inc., USA), which records penetration resistance (PR) in kilopascals (kPa) using a stainless steel 1.27 cm (0.5 inch) diameter cone (standard ASAE S313.3). Measurements were recorded at 2.5 cm intervals up to a maximum depth of 45 cm, and three insertions per subplot were performed and averaged to obtain a representative value. Because PR is highly influenced by soil water content (Vaz et al., 2011), a correction was applied using exponential models fitted by depth interval.

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The soil profile was divided into two depth groups: 0-15 cm and 15-45 cm, based on observed moisture gradients. For each depth group, a non-linear exponential model was fitted to describe the relationship between PR and volumetric water content (θ , $\text{m}^3 \text{m}^{-3}$):

$$PR = a \times e^{b \cdot \theta}$$

where PR is the observed penetration resistance (kPa), θ is volumetric water content ($\text{m}^3 \text{m}^{-3}$), a is a scaling parameter representing the expected PR value at $\theta = 0$, and b is the slope coefficient describing the sensitivity of PR to changes in soil water content, with more negative b values

indicating a stronger decrease in PR as soil water content increases. Parameters a and b were estimated for each depth group using the nls() function in R. Initial values for model fitting were set as the median PR value for a and -9 for b. The coefficient of determination (pseudo-R²) was calculated as:

$$R^2 = 1 - \frac{\sum (PR_{obs} - PR_{pred})^2}{\sum (PR_{obs} - \bar{PR}_{obs})^2}$$

Observed PR values were then corrected to account for moisture variability by normalizing them to the median water content for each depth group. The corrected values (*PR_{corr}*) were calculated using the equation proposed by Busscher et al. (1997):

$$PR_{corr} = PR_{obs} \times \frac{e^{b \cdot \theta_{ref}}}{e^{b \cdot \theta_{obs}}}$$

where θ_{ref} is the reference water content (median within each depth group), and θ_{obs} is the observed water content at the time of measurement.

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Grain

Harvesting was carried out using a commercial-grade combine harvester equipped with a calibrated yield monitor. Yield data were collected during harvest and processed to determine the average yield per plot.

Calculations

Glucose equivalent yield (kg GE ha⁻¹): was calculated by multiplying crop yield by a crop-specific glucose factor, which reflects the amount of glucose required to synthesize one kilogram of grain. The factors used were: 1.46 for soybean, 1.39 for corn, 1.36 for sorghum, and 1.27 for wheat (De Vries et al., 1983).

$$GE\ yield\ (kg\ ha^{-1}) = Yield\ (kg\ ha^{-1}) \times Glucose\ factor$$

Water use efficiency (WUE): was calculated as the ratio of yield, expressed in kilograms of glucose equivalent per hectare, to the total water supply (precipitation plus irrigation), using the following formula:

$$WUE = \frac{Yield\ (kg\ GE\ ha^{-1})}{Total\ Precipitation\ (mm) + Irrigation\ (mm)}$$

Nitrogen Use Efficiency (NUE): Nitrogen Use Efficiency (NUE) was calculated as the partial factor productivity of nitrogen, reflecting the grain output per unit of applied nitrogen. NUE was computed by dividing the grain yield, expressed in glucose equivalents (kg GE ha⁻¹), by the amount of nitrogen applied (kg N ha⁻¹) in each treatment:

$$NUE = \frac{Yield\ (kg\ GE\ ha^{-1})}{N\ applied\ (kg\ N\ ha^{-1})}$$

This metric provides a valuable indicator of the sustainability and efficiency of nitrogen fertilization practices across treatments (Dobermann, 2007).

Bulk density: to calculate the Carbon stocks the soil bulk density was determined for each plot and depth, for this, undisturbed soil cores were collected using a Giddings probe to a depth of approximately 120 cm and subdivided into six depth intervals: 0-5, 5-15, 15-30, 30-60, 60-90, and 90-120 cm. In cases where the maximum core depth was less than 120 cm (e.g., 117 cm), the actual recovered length was used for the volume calculation. Each segment was weighed, and the oven-dry mass was estimated using the gravimetric soil moisture content determined from a subsample. Bulk density (g cm⁻³) was calculated as the ratio of the estimated dry soil mass to the

corresponding core segment volume, based on the internal diameter of the Giddings probe and the actual segment length. The procedure followed the method described by Blake and Hartge (1986).

Statistical analysis

All statistical analyses were conducted in R (version 4.5.1; R Core Team, 2025) using the RStudio integrated development environment (version 2025.9.1.401; Posit Team, 2025). Data were checked for normality and homogeneity of variances prior to analysis. Treatment effects on response variables were evaluated using analysis of variance (ANOVA). Linear mixed-effects models were fitted with the lmer function from the lme4 package (Bates et al., 2015), incorporating random effects such as replication and/or year according to the experimental design. Model assumptions, including residual normality and variance homogeneity, were further assessed through diagnostic plots and functions available in the performance and car packages (Fox and Weisberg, 2019). When treatment effects were significant ($p < 0.05$), estimated marginal means (EMMs) were calculated using the emmeans package (Lenth, 2025), and pairwise comparisons were performed with Tukey's Honestly Significant Difference (HSD) test. Differences among treatments were represented using compact letter displays (CLD). All figures were generated primarily in R using the ggplot2, dplyr, and tidyr packages (Wickham, 2016; Wickham et al., 2023, 2024), applying a consistent theme across variables and years to ensure visual comparability of treatment effects.

Phase I - Soil properties

Two sets of analyses were performed for soil data collected in 2021 to evaluate long-term effects of rotational treatments on soil chemical and physical properties.

Soil chemical properties (0-5 and 5-15 cm):

Soil pH, organic matter (OM), cation exchange capacity (CEC), and extractable nutrients (NO_3^- -N, NH_4^+ -N, P, K, Ca, Mg, Na) were analyzed separately for the 0-5 cm and 5-15 cm depths. A linear mixed-effects model was fitted for each variable with rotation as a fixed effect and replication as a random effect:

$$Y_{ij} = \mu + \text{rotation}_i + (1 \mid \text{rep}_j)$$

Estimated marginal means (EMMs) were compared among rotations using Tukey-adjusted pairwise tests.

Depth-profiled variables (soil: 0-120 cm, compaction: 0-45 cm):

Total carbon (C) and total nitrogen (N) stocks (Mg ha^{-1}), and soil compaction (penetration resistance, MPa) were analyzed as depth-profiled measurements. For C and N stocks, six composited depth increments (0-5, 5-15, 15-30, 30-60, 60-90, 90-120 cm) obtained from Giddings cores were treated as repeated measures within plots.

For penetration resistance, measurements were recorded every 2.5 cm from 0 to 45 cm, representing a continuous soil profile. A linear mixed-effects model was fitted with rotation, depth, and their interaction as fixed effects, and replication and rotation $\times$ replication as random effects:

$$Y_{ijk} = \mu + \text{rotation}_i \times \text{depth}_j + (\mathbf{1} \mid \text{rep}_k) + (\mathbf{1} \mid \text{rep:rotation}_k)$$

Depth was treated as a continuous covariate for penetration resistance and as a categorical factor for C and N stocks. Pairwise comparisons of estimated marginal means were adjusted using Tukey's HSD method.

Phase II - Cover crop phase

From 2022 to 2024, a split-plot design was implemented to test the effects of cover crops within each crop rotation. The model included the main effects of rotation (whole-plot factor) and cover crop treatment (subplot factor), and their interaction:

$$Y_{ijkl} = \mu + \text{rotation}_i \times \text{cover}_j + (\mathbf{1} \mid \text{rep}_k) + (\mathbf{1} \mid \text{rep:rotation}_k) + (\mathbf{1} \mid \text{rep:rotation:plot}_k)$$

where rep:rotation and rep:rotation:plot represented random effects corresponding to whole- and sub-plot variability, respectively.

Grain yield, nitrogen use efficiency (NUE), water use efficiency (WUE), and soil moisture were analyzed using this model structure. EMMs were estimated for each rotation and cover-crop combination, and Tukey-adjusted pairwise comparisons were used to assess differences both within and across rotations.

Results and Discussion

Phase I (2015-2021): Soil changes after seven years of crop rotations

Previous studies have shown that continuous corn (CC) and simple rotations such as corn-wheat (CW) under limited irrigation often result in greater annual increases in soil organic carbon (SOC) and total nitrogen (TN), with reported gains of up to 717 kg SOC ha⁻¹ yr⁻¹ and 114 kg TN ha⁻¹ yr⁻¹ in CC, compared to lower accumulation rates in more diverse rotations such as

corn-wheat-sorghum-soybean (CWSSb) (Halvorson and Schlegel, 2012; Havlin et al., 1990; Al-Kaisi et al., 2005). These differences are generally attributed to higher residue inputs in corn-dominated systems, whereas rotations that include soybean (e.g., corn-soybean) or incorporate multiple low-residue phases tend to return less carbon to the soil, which may result in slower SOC and TN accumulation (Havlin et al., 1990; Al-Kaisi and Yin, 2005; Halvorson and Schlegel, 2012). In this study, total carbon (TC) stocks by depth (0-5, 5-15, 15-30, 30-60, 60-90, and 90-120 cm) did not differ among rotations (Figure 3.3; Tukey-adjusted within-depth comparisons, all $p > 0.05$). Similarly, no rotation effect was detected at the whole-profile scale (0-120 cm; $p = 0.996$). Profile-level estimated marginal means ($\pm$ SE) were 145 ± 9.7 (C), 142 ± 7.0 (C-Sb), 141 ± 7.0 (C-Sg), 141 ± 5.8 (C-W), and 140 ± 7.0 Mg ha⁻¹ (C-C-W), with overlapping 95% confidence intervals. These results were consistent in a sensitivity analysis restricting comparisons to plots under equivalent preceding crop conditions (i.e., C, C-Sg, C-Sb, and C-C-W following corn, and C-W following wheat), which likewise showed no significant differences among rotations at any depth or for total profile TC.

Rotations dominated by high-residue crops (corn, wheat, sorghum) are often reported to better maintain or increase soil nitrogen (TN) than rotations including soybean, a lower-residue crop (Havlin et al., 1990; Halvorson and Schlegel, 2012; Al-Kaisi et al., 2005). In this study, however, TN did not differ among rotations within any of the six depths (0-5, 5-15, 15-30, 30-60, 60-90, 90-120 cm) nor for the 0-120 cm profile total (ANOVA with Tukey-adjusted pairwise comparisons, $\alpha = 0.05$; Figure 3.4). Even so, the numerical ranking was consistent with expectations: C-Sb consistently ranked lowest across several layers and for the 0-120 cm total. Absolute differences were small relative to the standard errors (e.g., approximately 1.5 Mg N ha⁻¹ at the profile scale compared with SE values of about 0.9 to 1.3 Mg N ha⁻¹), and no pairwise

contrast was significant after Tukey adjustment across five rotations and six depths. Moreover, the mixed model with unequal replication resulted in modest effective degrees of freedom, leading to wider confidence intervals. Together, these factors likely contributed to the consistently lower TN observed in C-Sb remaining a non-significant tendency.

Detecting rotation-driven shifts in soil C/N typically requires long observation windows: SOC (and often TN) changes slowly, with detectable differences often needing ~6-10 years even under large input changes and intensive sampling (West and Post, 2002; Smith, 2004; Poeplau and Don, 2015); thus, rotation contrasts may remain statistically indistinguishable within seven years.

Crop diversification and reduced tillage are commonly linked to gains in soil organic matter (OM) via residue retention and microbial activity (Havlin et al., 1990; Franzluebbers, 2002; West and Post, 2002; Al-Kaisi and Yin, 2005; Blanco-Canqui and Lal, 2008), and in this experiment the rotations that included wheat comprised a larger share of no-till years (whereas corn, sorghum and soybean phases were strip-tilled most of the time). Yet OM did not differ significantly among rotations (Fig. 3.6). Moreover, the numerical trend ran in the opposite direction: at 5-15 cm, continuous corn showed the highest mean OM (~4.0%) while the other rotations ranged from 2.65 to 3.18%; pairwise contrasts with continuous corn approached significance ($p = 0.055$ to 0.069) but did not remain significant after Tukey adjustment. At 0-5 cm, means overlapped (EMMs ≈ 4.33 to 5.10%). This lack of response is consistent with previous findings showing that no-till does not always increase soil organic carbon in wheat-based systems, particularly under wheat-fallow conditions (West and Post, 2002). Overall, rotation-level differences in OM were small relative to variability over seven years, with a

numerically higher OM in continuous corn consistent with greater annual residue inputs (Bowles et al., 2020; Giacometti et al., 2021).

At 0-5 cm, soil pH differed among rotations, with continuous corn and C-C-W exhibiting the lowest values, C-Sb the highest, and C-Sg and C-W intermediate (Figure 3.6, lower panels). No differences were detected at 5-15 cm. This surface-limited pattern is consistent with the greater cumulative acidification from ammoniacal N inputs in rotations with a high frequency of corn (Table 3.3): in 2015-2020, corn routinely received sidedress N ($\sim 168 \text{ kg N ha}^{-1}$) in addition to pre-plant applications, and in 2021 it received $\sim 112 \text{ kg N ha}^{-1}$ at planting plus $\sim 67 \text{ kg N ha}^{-1}$ sidedress. Nitrification of these inputs releases H^+ , and subsequent nitrate-driven leaching of base cations (Ca^{2+} , Mg^{2+} , K^+) further lowers pH near the surface (Tisdale et al., 1985), particularly under reduced soil mixing. By contrast, C-Sb includes soybean years without N fertilizer, reducing the net acidifying pressure and aligning with its higher pH at 0-5 cm.

Patterns in mineral N support this interpretation. At 0-5 cm, both NO_3^- -N and NH_4^+ -N tended to be higher in corn-intensive systems (C, C-C-W) and lower in C-Sb; at 5-15 cm these contrasts weakened and only a small NH_4^+ difference persisted (Figure 3.7). The signal at the surface likely reflects the placement of N (pre-plant and sidedress via streamer bars; Table 3.3), along with short-term mineralization and immobilization processes in the surface soil.

For plant-available P, no rotation effect was observed at either depth (Figure 3.7), which is consistent with broadly similar P applications across treatments (e.g., pre-plant P and S applied to all crops in 2015-2020; updated rates in 2021; Table 3.3). Exchangeable K differed only at 0-5 cm, where C-Sb showed the highest values and C-W the lowest (Figure 3.7). This contrast is consistent with surface stratification under reduced disturbance and with differences in seasonal K cycling among rotations (Mallarino et al., 2013). Because soil sampling was conducted in

November, K released from soybean residues after harvest may have accumulated near the soil surface during the fallow period in C-Sb. In contrast, winter wheat had already been established in C-W and may have already begun taking up part of the available K from the surface soil.

Among the base cations and capacity indices (Ca, Mg, Na, CEC), rotations were largely similar (Figure 3.8). A small Mg difference at 5-15 cm ($C-W > C-Sg$) was the only notable contrast and is likely of limited agronomic significance, plausibly reflecting spatial heterogeneity and differences in residue cycling rather than targeted amendments (none applied; Table 3.3).

Overall, the significant rotation effects were modest and concentrated in the surface layer, reflecting the history of N inputs and residue recycling rather than broad changes in P supply or exchange capacity.

Phase II (2015-2021): Effect of cover crops on Yield, WUE and NUE

Despite two drier-than-normal, rainfed years (2022-2023; Fig. 3.1), introducing cover crops did not reduce whole-rotation productivity: three-year, rainfed glucose-equivalent (GE) grain yield least-squares means were statistically similar between the subplots with and without cover crops for every rotation, and the cover $\times$ rotation interaction was not significant (Fig. 3.13). In other words, the ranking among rotations persisted, but introducing cover crops did not shift whole-system output over the 2022-2024 window.

Crop-specific responses were small and rotation-dependent (Fig. 3.14). Within the corn-soybean (C-Sb) rotation, soybean yield was lower with cover crops (Tukey letters “a” vs “b”), whereas corn (in all rotations) and sorghum (in C-Sg) showed no detectable cover effect. For wheat, a modest difference appeared in C-W only (letters shown), while C-C-W did not differ between cover treatments. These effects were confined to a subset of crop $\times$ rotation panels and

were modest in magnitude relative to between-season variability. Under rainfed conditions, such patterns are consistent with known trade-offs (e.g., occasional soil-water drawdown by the cover prior to planting and short-term N immobilization in high-residue seedbeds) without a measurable penalty at the whole-rotation scale during the three-year evaluation period.

Water-use efficiency (WUE) expressed as glucose-equivalent yield per unit water supply, showed the same ordering as total yield across rotations, with continuous corn highest, C-Sg and C-C-W close behind, C-W intermediate, and C-Sb lowest (Fig. 3.15). Introducing cover crops did not change WUE within any rotation: Tukey-adjusted contrasts between cover-crop levels were non-significant ($\alpha = 0.05$), and numerical differences were small relative to the standard errors. Taken together with the dry, rainfed conditions in 2022-2023 (Fig. 3.1), these results indicate that even under limited water availability, the inclusion of cover crops did not reduce productivity in any of the rotations over 2022-2024.

Across rotations, introducing cover crops did not alter system-level nitrogen use efficiency ($NUE_{3y} = \Sigma GE / \Sigma N$). Least-squares means for GE-based NUE were statistically similar between cover-crop subplots within each rotation (Tukey, $\alpha = 0.05$; Fig. 3.16). Numerically, NUE tended to be higher in rotations that include soybean or sorghum (C-Sb, C-Sg) and lower in corn-heavy sequences (C, C-C-W), reflecting lower N inputs per unit glucose-equivalent yield when non-fertilized soybean is part of the sequence.

Crop-specific analyses revealed a single significant effect: in continuous corn, corn NUE was lower with cover crops than without (different Tukey letters in the corn panel for C; Fig. 3.17). Because N inputs were the same between treatments, this reduction in NUE indicates that corn yield was slightly lower with cover crops, although the magnitude of the yield difference was not large enough to be reflected as a significant effect on productivity at the rotation scale.

For corn in the other rotations, and for sorghum and wheat, cover-crop effects on crop-level NUE were not significant. Taken together, the three-year rainfed results indicate that cover crops did not change NUE at the whole-rotation scale, while crop-level responses were limited and context-dependent, consistent with occasional early-season N immobilization or water drawdown affecting corn in continuous systems but not producing a detectable rotation-scale penalty over 2022-2024.

Conclusion

Under south-central Nebraska conditions and limited irrigation, crop rotation had only modest short-term effects on soil properties, suggesting that seven years may be insufficient to detect meaningful changes in soil C and N stocks across these systems. Most measured soil properties were similar among rotations, and the clearest long-term response was greater surface acidification in corn-intensive sequences, highlighting the importance of monitoring pH where corn frequency and N fertilization rates are high.

The introduction of cover crops did not reduce whole-rotation productivity, WUE, or system-level NUE, even during relatively dry years. Although some crop-specific responses were observed, these effects were limited and did not translate into lower overall system performance.

Overall, the results highlight the importance of long-term experiments for detecting gradual soil responses to crop rotation under limited irrigation and for determining whether short-term crop-specific responses to cover crops persist over time.

Commented [KR19]: Lots of repetition from R&D section. consider condensing to focus more exclusively on conclusions, not so much summarizing results.

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Tables and Figures

Table 3.1 Particle-size distribution (%) and USDA texture class by depth at the experimental site.

Depth	Clay	Silt	Sand	Texture
cm	----- % -----			
0-5	22.0	54.7	23.3	silty loam
5-15	26.7	54.3	19.0	silty loam
15-30	34.3	48.0	17.7	silty clay loam
30-60	29.3	52.0	18.7	silty clay loam
60-90	24.7	53.3	22.0	silty loam
90-120	20.3	58.0	21.7	silty loam

Note. Percentages are by mass. Texture classes follow the USDA textural triangle. Values are means of three experimental blocks; samples were collected in 2021 with a Giddings-core sampler. Depths are interval bounds (cm).

Table 3.2 Annual irrigation (mm) by crop and rotation during Phase I (2015-2021) at the experimental site. Yearly totals are shown for each crop-rotation combination along with the 2015-2021 mean.

Crop	Rotation	Annual Irrigation							Average
		2015	2016	2017	2018	2019	2020	2021	
		mm							
Corn	C	89	97	25	25	0	0	100	48
Corn	C - Sg	140	114	38	25	0	0	100	60
Corn	C - Sb	89	89	51	25	0	0	94	50
Corn	C - W	140	114	76	25	0	0	71	61
Corn	C - C - W	114	97	57	25	0	0	86	54
Sorghum	C - Sg	51	51	76	0	0	0	100	40
Soybean	C - Sb	89	89	51	25	0	0	94	50
Wheat	C - C - W	0	0	0	0	0	0	0	0
Wheat	C - W	0	0	13	0	0	0	0	2

Note. Units are millimeters (mm). 0 indicates no irrigation applied that year. Rotations: C = continuous corn; C-Sg = corn-sorghum; C-Sb = corn-soybean; C-W = corn-wheat; C-C-W = corn-corn-wheat.

Table 3.3 Fertilizer application details by year and crop: placement, rate (kg ha⁻¹), timing, and nutrient type. (N = Nitrogen, P = Phosphorus, S = Sulfur, Zn = Zinc; placement refers to method/location of fertilizer application).

Year	Crop	Time & Place		Rate				Date
				N	P	S	Zn	
				----- kg ha-1 -----				
2015 - 2020	Wheat	Side-dressing	Streamer bars	112	67.3	28.0		NA
2015 - 2020	Corn	Pre-planting	Streamer bars		67.3	28.0	0.56	NA
2015 - 2020	Corn	Side-dressing	Streamer bars	168				NA
2021	Wheat	Side-dressing	Streamer bars	101	44.8	22.4		12-Apr-21
2021	Corn, Soybean and Sorghum	Pre-planting	Streamer bars		56.0	23.3	0.23	26-Apr-21
2021	Corn and Sorghum	At planting	Streamer bars	112				7-May-21
2021	Corn	Side-dressing	Streamer bars	67				22-Jun-21
2022	Corn, wheat and Sorghum	Pre-planting	Streamer bars	112	44.8	18.5	0.18	12-Apr-22
2022	Corn and Sorghum	Side-dressing	y-drop	67				24-Jun-22
2022	Soybean	At planting	with planter	22	44.8	18.5	0.18	22-May-22
2023	Wheat	Side-dressing	Streamer bars	67				21-Apr-23
2023	Corn, Wheat, Sorghum, Soybean	Side-dressing	Streamer bars	33	67.3	28.0		23-May-23
2023	Corn	Side-dressing	y-drop	168				23-Jun-22
2024	Corn and Sorghum	At planting	with planter	33	67.3	28.0	0.28	17-May-24
2024	Soybean	At planting	with planter	33	67.3	28.0	0.28	8-May-24
2024	Corn, Wheat, Sorghum, Soybean	Side-dressing	Streamer bars	78				16-May-24
2024	Corn	Side-dressing	y-drop	168				19-Jun-24
2024	Sorghum	Side-dressing	y-drop	75				25-Jun-24

Table 3.4 Cover-crop species, preceding crops, planting dates, and seeding rates during Phase II (2021-2024).

Year	Preceding crop	Cover crop	Planting date	Termination date	Planting rate --- kg ha ⁻¹ ---
2021	wheat, soybean, sorghum, and corn	cereal rye	10/10/2021	04/28/2022	89.7
2022	wheat, soybean, sorghum, and corn	cereal rye	11/04/2022	05/20/2023	89.7
2023	sorghum and corn	cereal rye	10/19/2023	-	89.7
2023	soybean	daikon radish, hairy vetch, oats and wheat	09/26/2023	-	3.4, 16.8, 16.8 and 22.4
2023	wheat	cereal rye, daikon radish, hairy vetch and oats	08/28/2023		16.8, 2.2, 20.2 and 20.2
2024	corn	cereal rye	10/23/2024		89.7
2024	sorghum and soybean	crimson clover, hairy vetch and oats	10/04/2024		16.8, 22.4 and 22.4
2024	wheat	cereal rye, daikon radish, hairy vetch and oats	08/25/2024		16.8, 2.2, 16.8 and 20.2

Note. Seeding rates are in kilograms per hectare (kg ha⁻¹). Years refer to the year of cover-crop establishment. “Preceding crop” denotes the cash crop harvested immediately before cover-crop planting. Multiple rows within a year indicate different species and/or preceding-crop combinations. Planting dates are calendar dates (day-month).

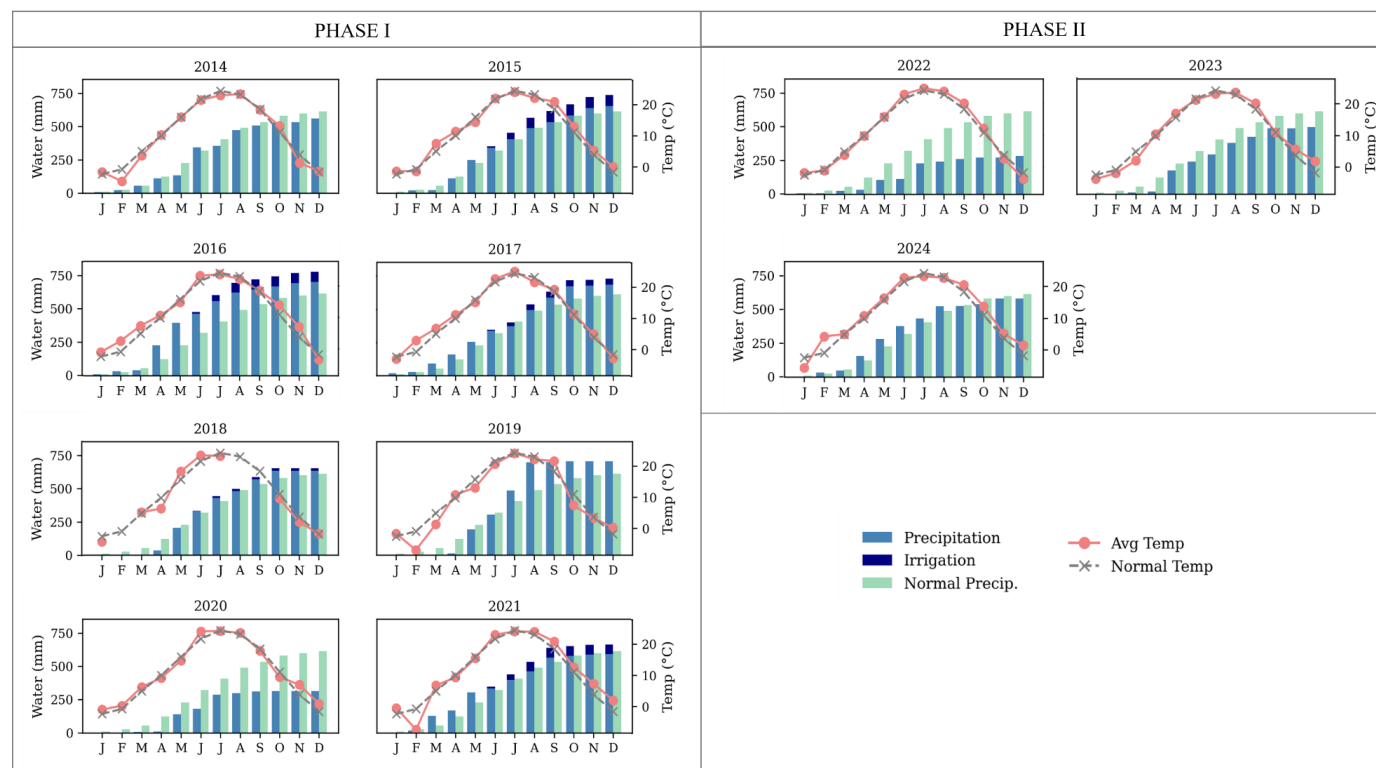


Figure 3.1 Accumulated monthly water supply (precipitation + irrigation, mm) and average monthly temperature at the Gothenburg Learning Center Station, shown separately for (a, left) Phase I (2014-2021) and (b, right) Phase II (2022-2024). Dark blue bars represent irrigation, light blue bars precipitation, and green bars the 1991-2020 monthly precipitation normal (NOAA, 1991). Red lines with circles represent average monthly temperature for each year, and gray dashed lines with crosses represent the 1991-2020 temperature normal.

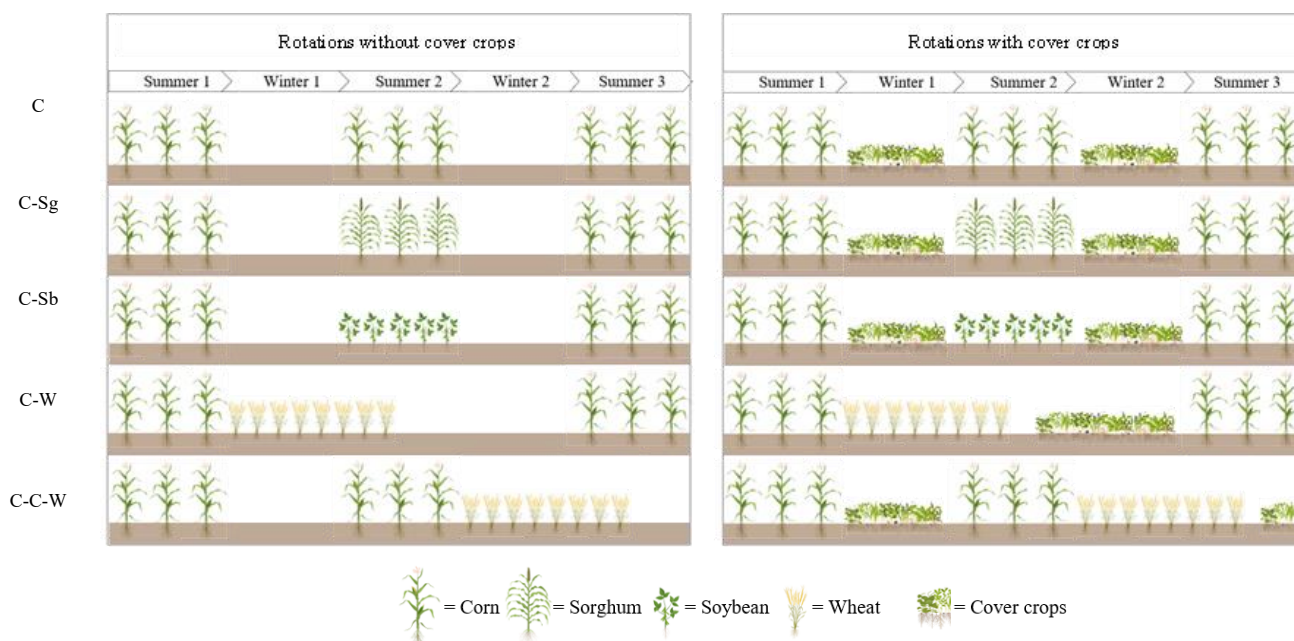


Figure 3.2 Conceptual diagram of the five corn-based rotations with and without cover crops under limited irrigation. The left panel (no cover crops) represents Phase I (2015-2021) and, in Phase II (2021-2024), the no-cover half of each split plot; the right panel represents the cover-crop half of each split plot in Phase II. Rows correspond to each rotation-continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Columns indicate the seasonal sequence. Icons denote the crop present in each season (corn, sorghum, soybean, wheat, cover crops). Sequences were implemented and repeated annually on the same plots.

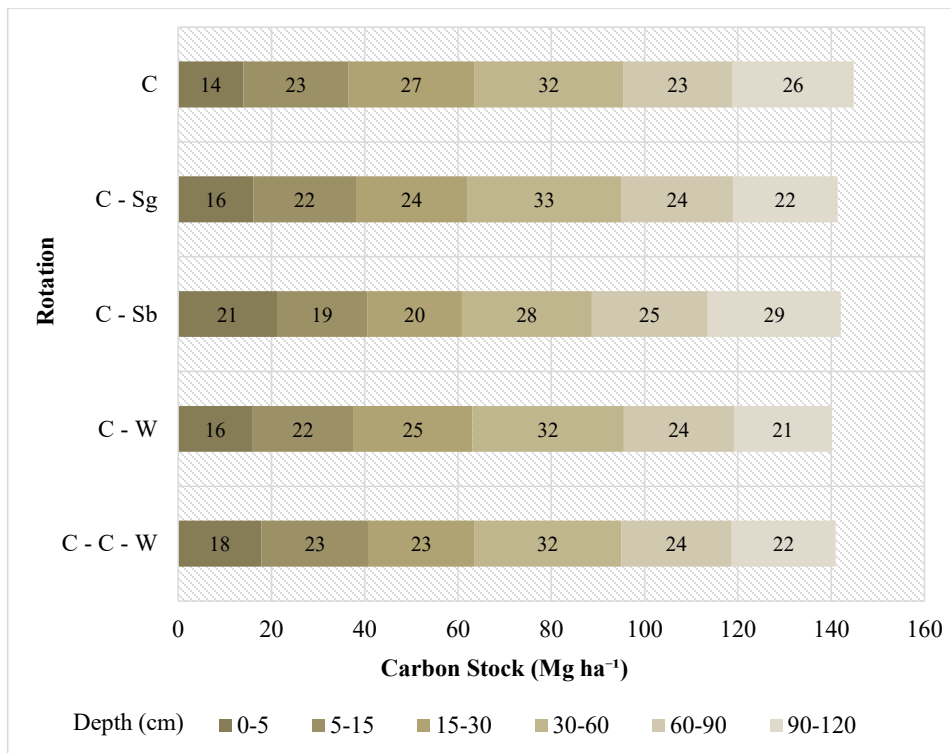


Figure 3.3 Carbon stock (Mg ha^{-1}) after seven years (2021) across five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Bars are stacked to show contributions from six soil depths: 0-5, 5-15, 15-30, 30-60, 60-90, and 90-120 cm. Values within each segment represent the carbon stock (Mg ha^{-1}) for the corresponding depth layer. No significant differences among rotations were detected at any depth (ANOVA, Tukey-adjusted pairwise comparisons, $\alpha = 0.05$).

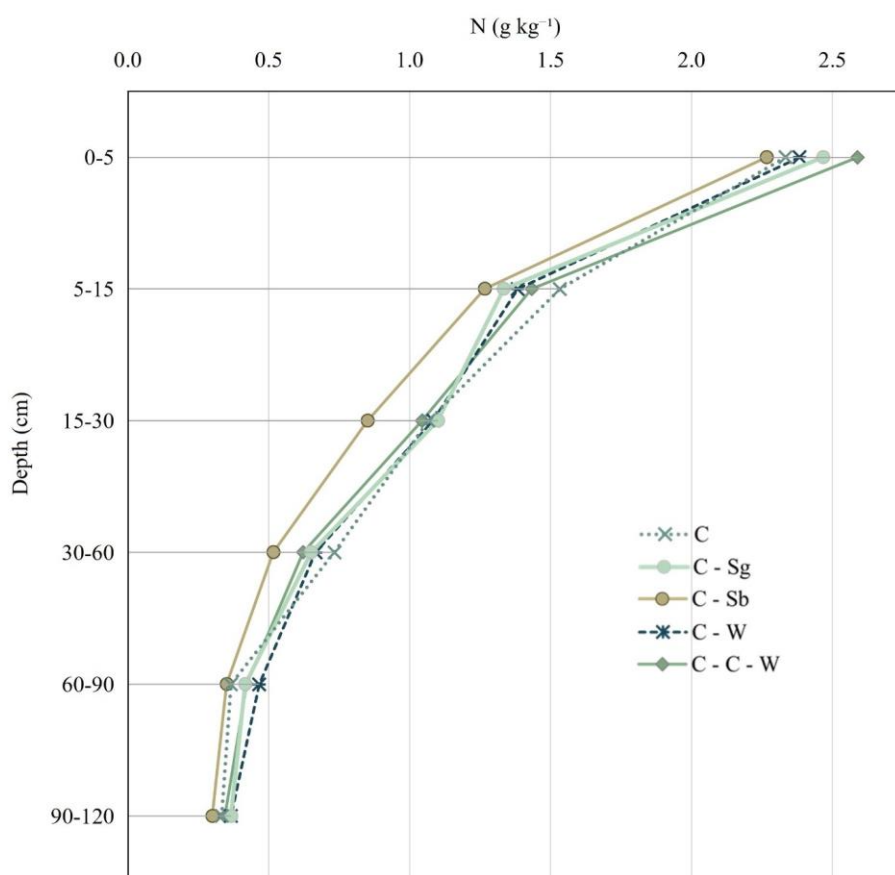


Figure 3.4 Total nitrogen concentration (g kg^{-1}) by soil depth (0-5, 5-15, 15-30, 30-60, 60-90, and 90-120 cm) after seven years (2021) across five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Lines represent mean values for each rotation. Statistical analysis showed no significant differences among rotations at any depth or for the total 0-120 cm profile (ANOVA with Tukey-adjusted pairwise comparisons, $\alpha = 0.05$).

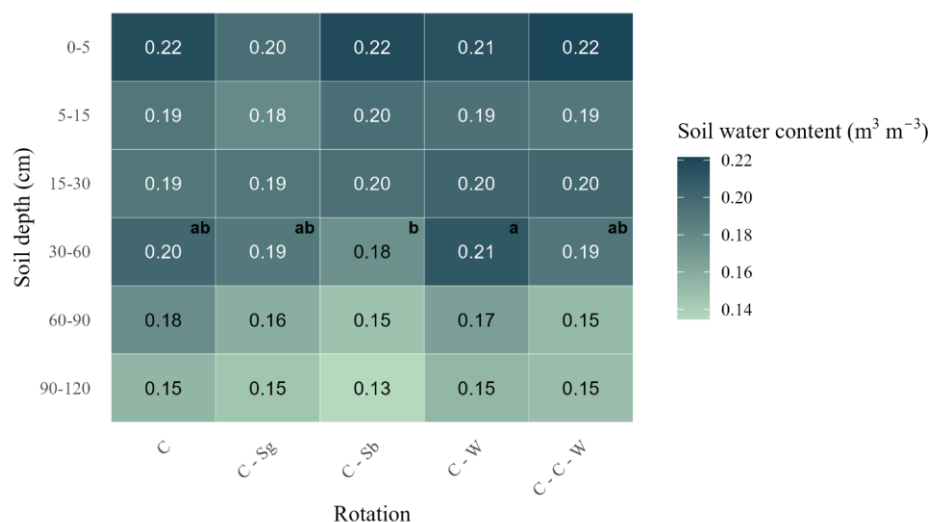


Figure 3.5 Soil water content ($\text{m}^3 \text{m}^{-3}$) by soil depth (0-5, 5-15, 15-30, 30-60, 60-90, and 90-120 cm) across five corn-based rotations after seven years (2021): continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Values represent model-adjusted means (LMM) for each rotation and depth. Numbers inside tiles indicate mean values, while letters denote significant differences among rotations within a given depth (Tukey-adjusted pairwise comparisons, $\alpha = 0.05$).

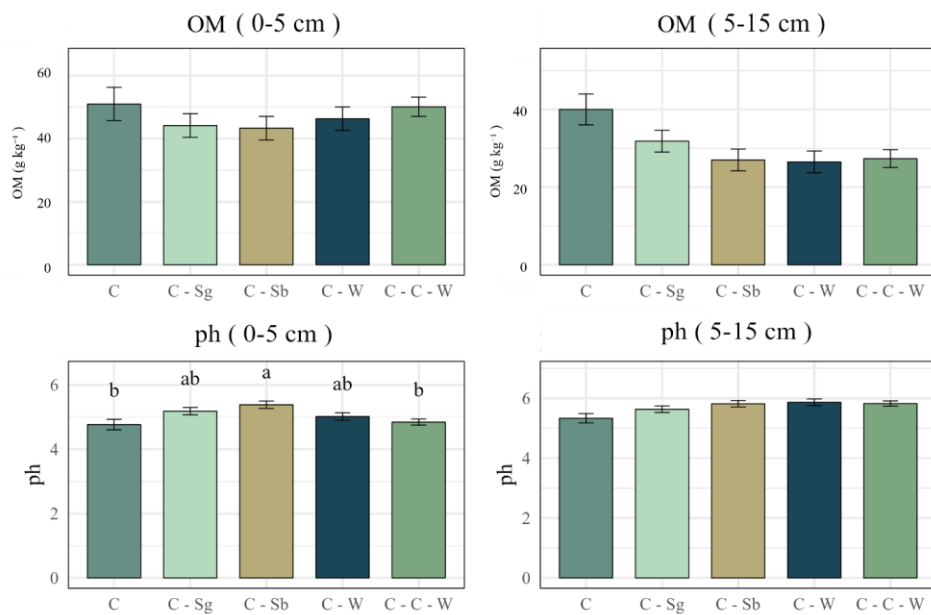


Figure 3.6 Soil organic matter (OM, top panels) and pH (bottom panels) measured in 2021 after seven years under five corn-based crop rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Bars represent treatment means, and vertical lines indicate ± 1 standard error of the mean (SEM). Measurements were taken at two soil depths: 0-5 cm (left panels) and 5-15 cm (right panels). Different letters indicate statistically significant differences among treatments within each panel based on Tukey-adjusted comparisons ($\alpha = 0.05$); treatments with no letters were not statistically different.

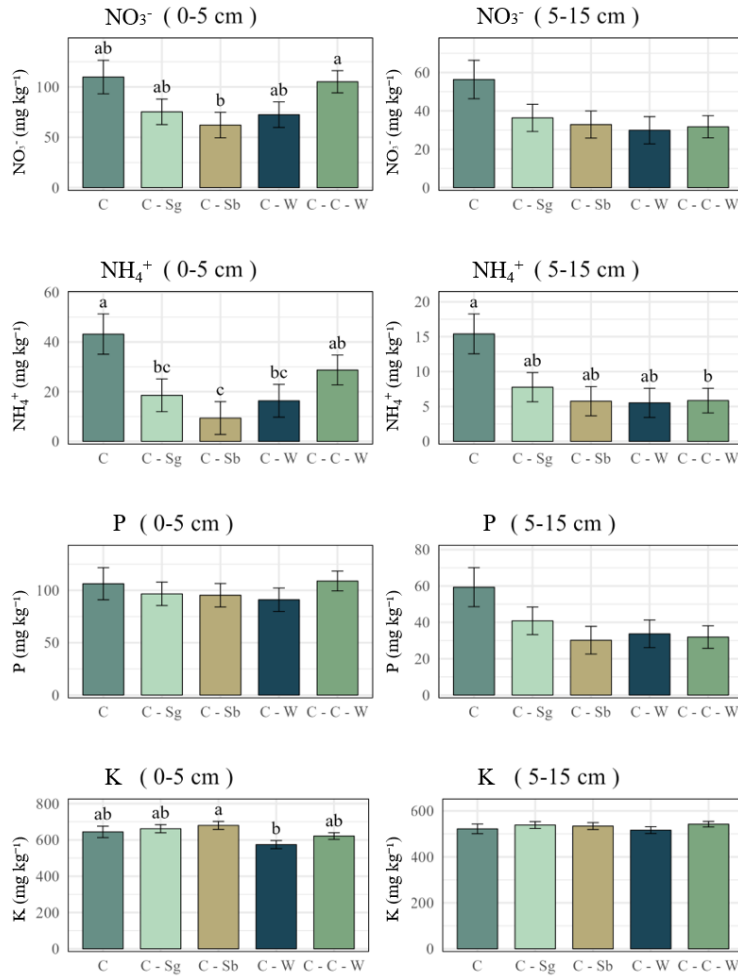


Figure 3.7 Soil inorganic nitrogen-nitrate-N (NO₃⁻-N) and ammonium-N (NH₄⁺-N) (top panels)- and soil phosphorus (P) and potassium (K) (bottom panels) measured in 2021 after seven years under five corn-based crop rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Bars represent treatment means, and vertical lines indicate ±1 standard error of the mean (SEM). Measurements were taken at two soil depths: 0-5 cm (left panels) and 5-15 cm (right panels). Different letters indicate statistically significant differences among treatments within each panel based on Tukey-adjusted comparisons (α = 0.05); treatments with no letters were not statistically different.

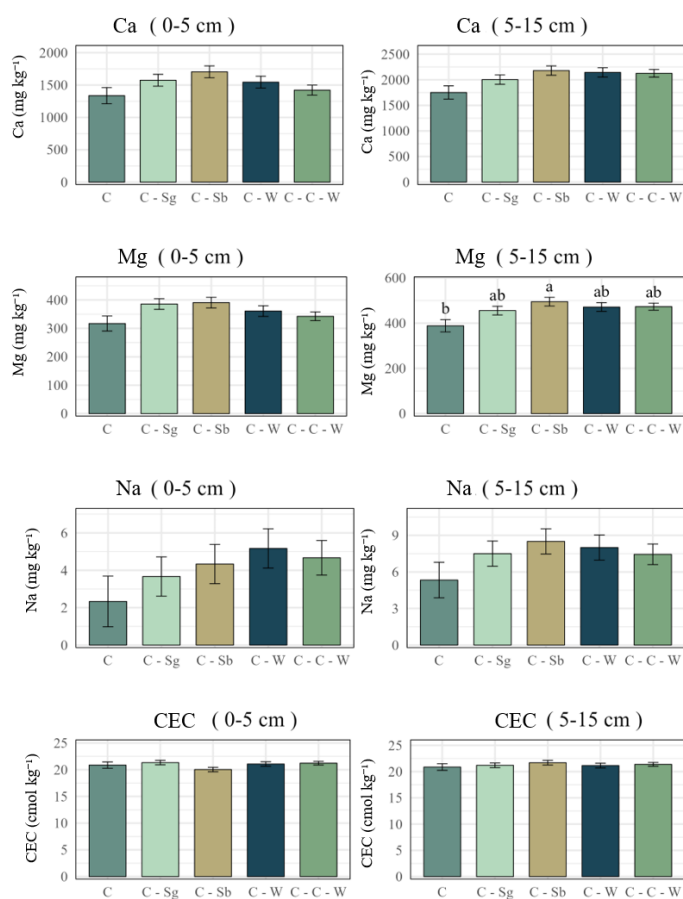


Figure 3.8 Soil exchangeable cations-calcium (Ca) and magnesium (Mg) (top panels)-and sodium (Na) and cation exchange capacity (CEC) (bottom panels) measured in 2021 after seven years under five corn-based crop rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Bars represent treatment means, and vertical lines indicate ± 1 standard error of the mean (SEM). Measurements were taken at two soil depths: 0-5 cm (left panels) and 5-15 cm (right panels). Cation concentrations are expressed as mg kg^{-1} and CEC as cmolc kg^{-1} . Different letters indicate statistically significant differences among treatments within each panel based on Tukey-adjusted comparisons ($\alpha = 0.05$); treatments with no letters were not statistically different.

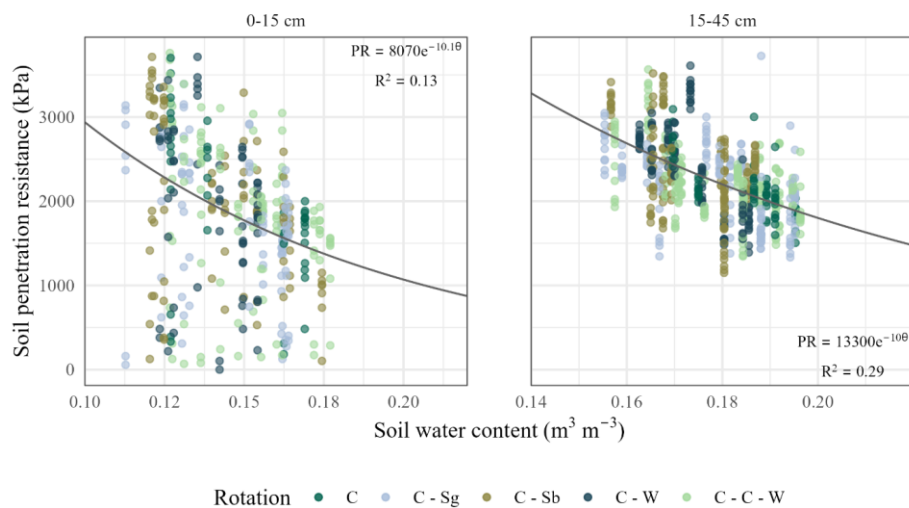


Figure 3.9 Relationship between soil penetration resistance (kPa) and volumetric soil water content ($\text{m}^3 \text{m}^{-3}$) for two depth intervals: 0-15 cm (left) and 15-45 cm (right). Points are individual observations; lines show the fitted exponential regressions used to estimate the moisture sensitivity parameter (b) and to normalize PR to a common reference water content (θ_{ref}) prior to comparing crop-rotation effects.

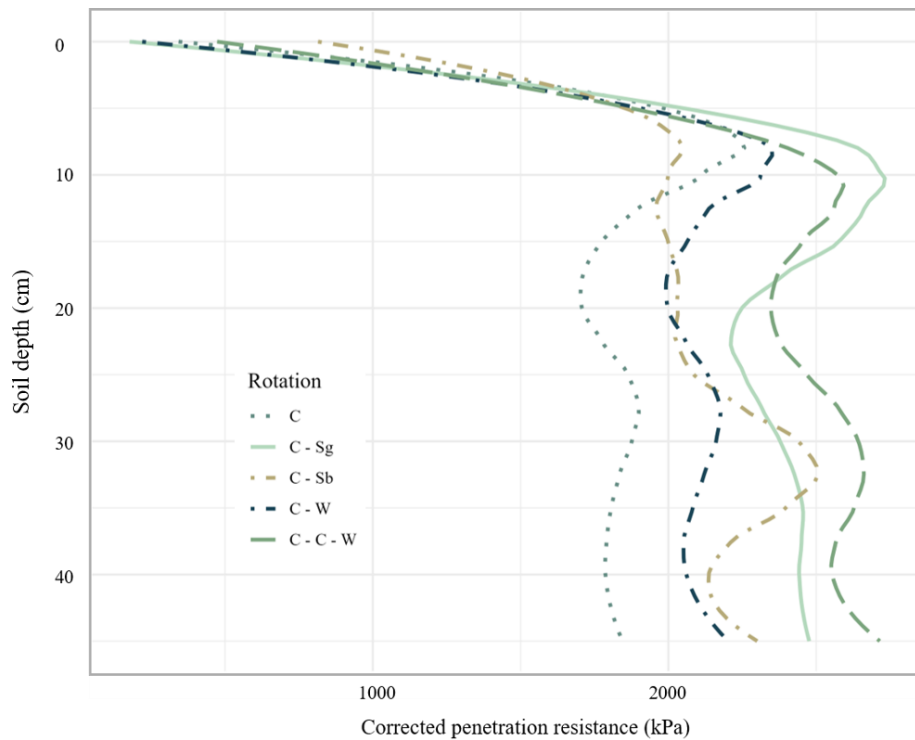


Figure 3.10 Depth profiles of corrected soil penetration resistance (kPa) from 0-45 cm in 2021 after seven years under five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Data exclude cover-crop plots; C, C-Sg, C-Sb, and C-C-W were evaluated on fallow after corn, and C-W on fallow after wheat. Curves show rotation means normalized to a common reference volumetric water content (θ_{ref} ; see Methods). Higher values indicate greater soil strength/compaction. A mixed-effects model (quadratic depth; random effects for block and profile) found depth significant but no rotation or rotation $\times$ depth effects (Tukey-adjusted, $\alpha = 0.05$).

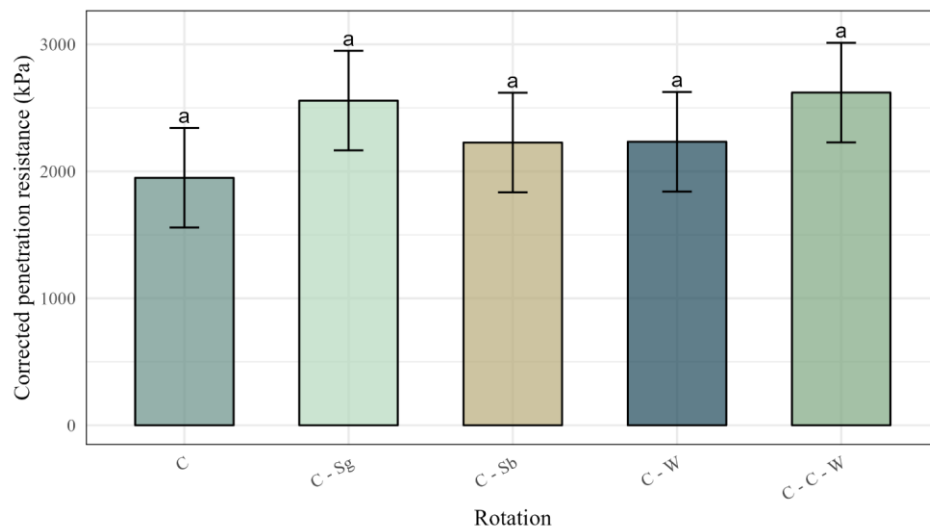


Figure 3.11 Mean corrected penetration resistance (kPa) averaged over the 0-45 cm profile in 2021 after seven years under five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Data exclude cover-crop plots; C, C-Sg, C-Sb, and C-C-W were evaluated on fallow following corn, and C-W on fallow following wheat. Values were normalized to a common reference volumetric water content (θ_{ref} ; see Methods). Error bars are $\pm$ SE of estimated marginal means ($n = 3$ blocks). No significant differences among rotations were detected (linear mixed model with rotation fixed; quadratic depth covariate with rotation $\times$ depth interaction; random intercepts for block and profile and an uncorrelated random slope of depth by profile; Tukey adjustment, $\alpha = 0.05$).

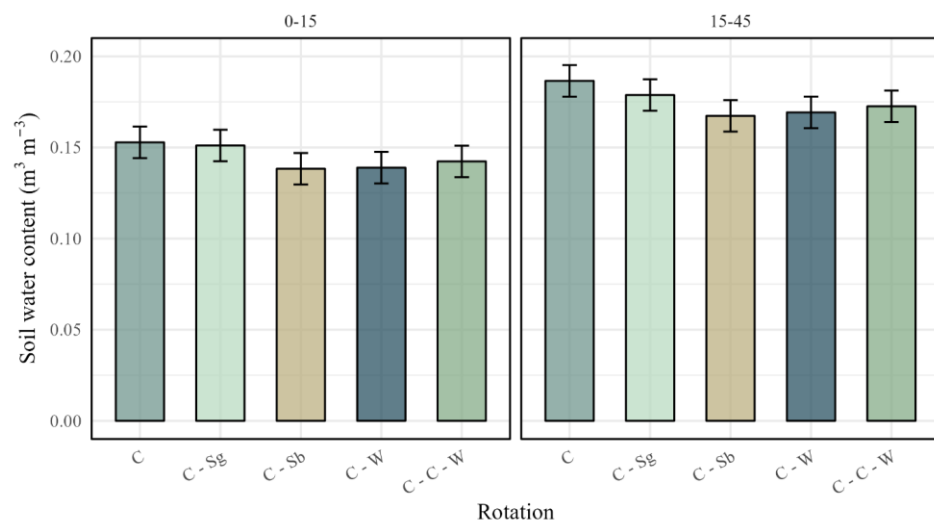


Figure 3.12 Soil water content (θ , $\text{m}^3 \text{m}^{-3}$) at two depth intervals (0-15 cm and 15-45 cm) under five corn-based rotations: continuous corn (C), corn-sorghum (C-Sg), corn-soybean (C-Sb), corn-wheat (C-W), and corn-corn-wheat (C-C-W). Hand samples were collected in spring 2022 to support corrections of penetration-resistance measurements. Data exclude cover-crop plots; C, C-Sg, C-Sb, and C-C-W were evaluated on fallow following corn, and C-W on fallow following wheat. Bars show estimated marginal means from a linear mixed-effects model with rotation $\times$ depth-group fixed effects and random intercepts for block and plot. Error bars are $\pm$ SE. No Tukey-adjusted pairwise differences among rotations were detected within either depth interval ($\alpha = 0.05$).

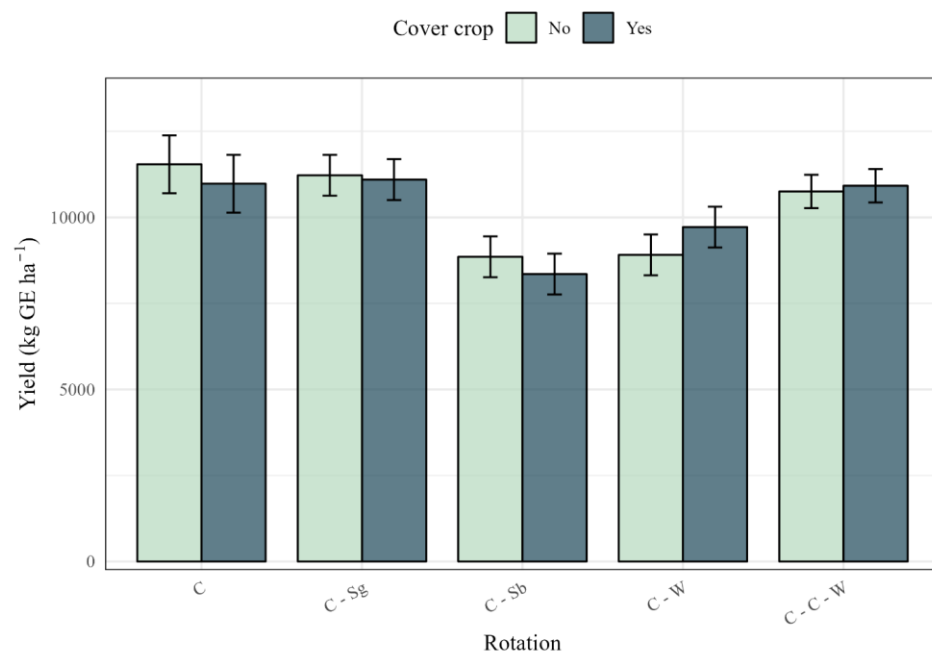


Figure 3.13 Glucose-equivalent grain yield (kg GE ha⁻¹) averaged across 2022-2024 for five corn-based rotations-C, C-Sg, C-Sb, C-W, and C-C-W-with (Yes) and without (No) cover crops. All plots were rainfed (no supplemental irrigation). Bars are split-plot linear mixed-model least-squares means; error bars show ± 1 SE of the LS-means. Fixed effects were rotation, cover crop, and their interaction; random effects were block, block $\times$ rotation (whole-plot), and block $\times$ rotation $\times$ plot_pair (subplot pairing). Within each rotation, cover-crop means were compared by Tukey; no significant differences were detected ($\alpha = 0.05$).

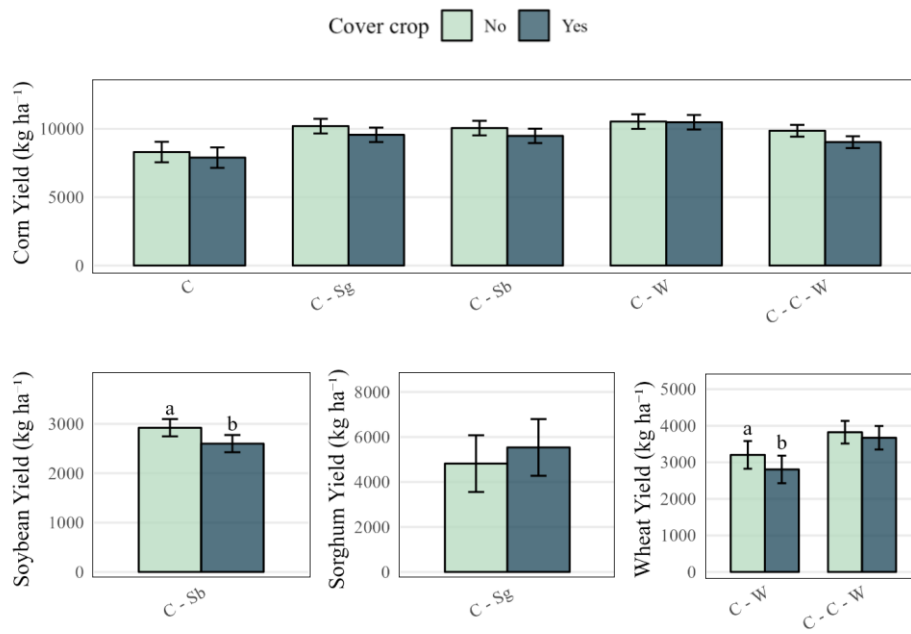


Figure 3.14 Crop-specific yields (kg ha⁻¹) for the crops present in each rotation-corn (C, C-Sg, C-Sb, C-W, C-C-W), soybean (C-Sb), sorghum (C-Sg), and wheat (C-W, C-C-W). Bars show split-plot linear mixed-model least-squares means (LS-means); error bars indicate ± 1 standard error of the LS-means. Models were fit separately by crop with fixed effects for rotation, cover crop, and their interaction, and random effects for block and block $\times$ rotation. Letters denote Tukey-adjusted differences between cover-crop levels within a rotation ($\alpha = 0.05$); panels without letters indicate no significant difference. All plots were rainfed; no supplemental irrigation was applied during 2022-2024.

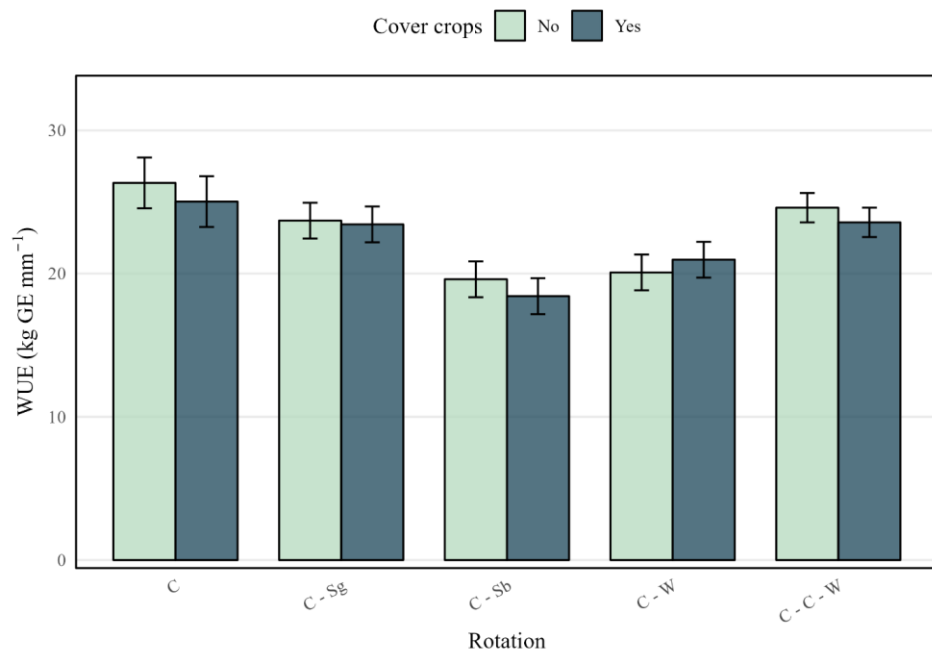


Figure 3.15 Water-use efficiency (WUE; kg GE mm⁻¹) for five corn-based rotations-C, C-Sg, C-Sb, C-W, and C-C-W-with and without cover crops (three-year means, 2022-2024). Bars are least-squares means from a split-plot linear mixed model with fixed effects of rotation, cover crop, and their interaction, and random effects of block, block×rotation, and block×rotation×plot_pair. Error bars show ±1 SE of the LS-means. Within each rotation, cover-crop levels were compared with Tukey-adjusted contrasts; no significant differences were detected ($\alpha = 0.05$).

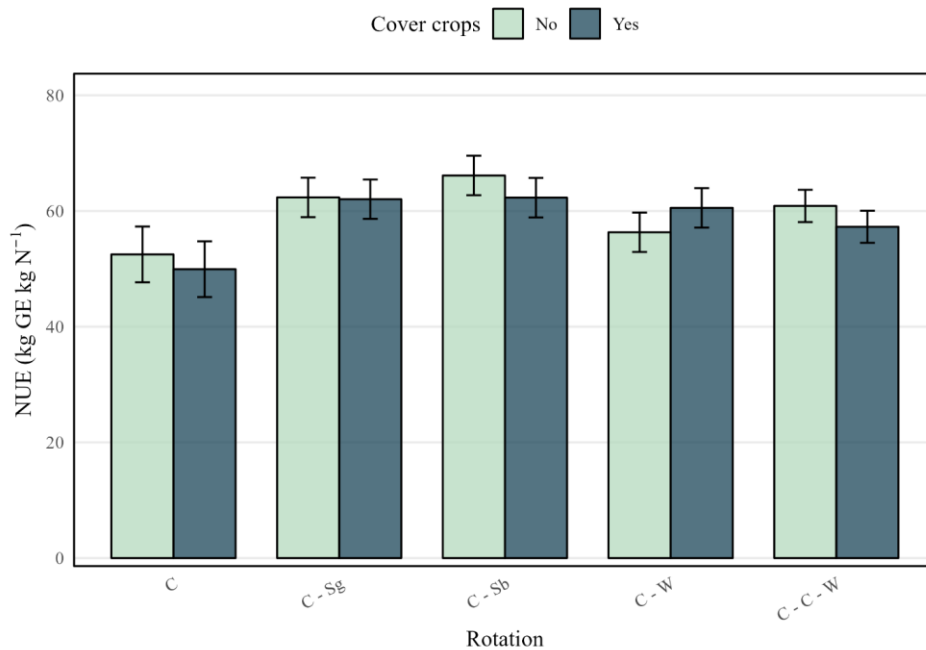


Figure 3.16 Nitrogen use efficiency (NUE; kg GE kg N⁻¹) for five corn-based rotations-C, C-Sg, C-Sb, C-W, and C-C-W-with and without cover crops (three-year means, 2022-2024). NUE was computed at the subplot level as the ratio of the 3-yr cumulative glucose-equivalent grain yield to the 3-yr cumulative N applied ($NUE_{3y} = \Sigma GE / \Sigma N$). Bars show least-squares means from a split-plot linear mixed model with fixed effects of rotation, cover crop, and their interaction, and random effects of block, block×rotation, and block×rotation×plot_pair. Error bars denote ±1 SE of the LS-means. Within each rotation, cover-crop treatments were compared using Tukey-adjusted contrasts; no significant differences were detected ($\alpha = 0.05$). All plots were rainfed (no supplemental irrigation).

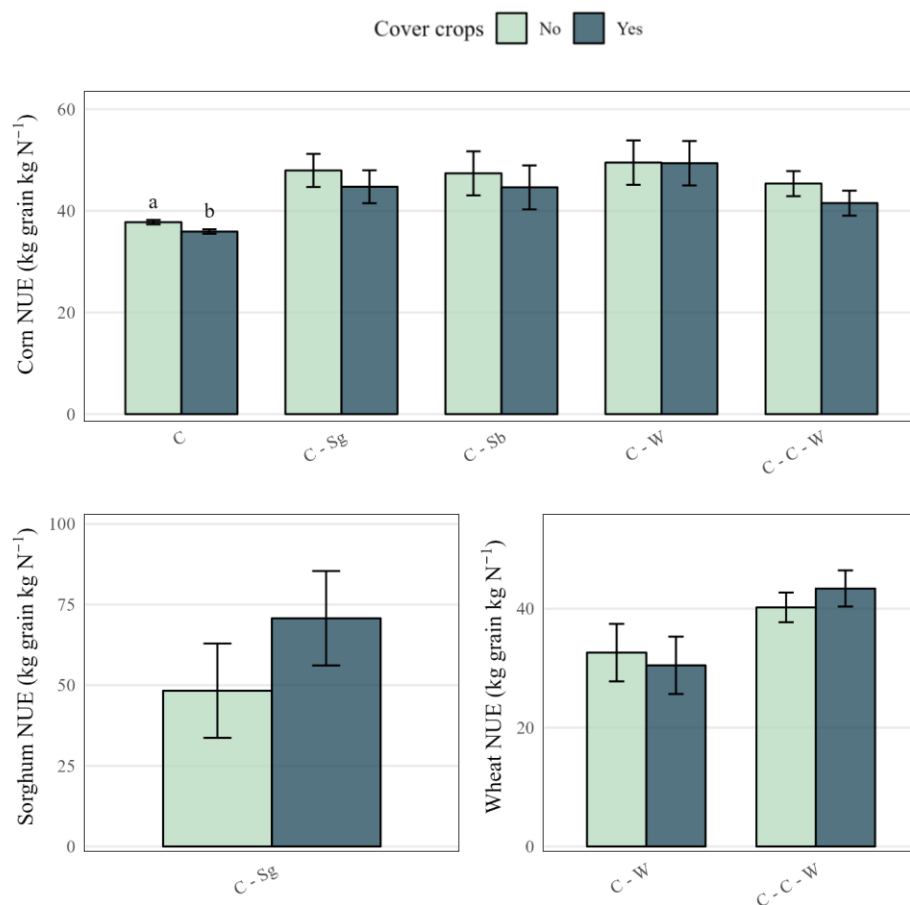


Figure 3.17 Nitrogen use efficiency (NUE; kg grain kg N⁻¹) by rotation and cover-crop treatment, shown separately for (top) corn, (bottom left) sorghum, and (bottom right) wheat. NUE was computed per subplot as the three-year total grain yield (kg ha⁻¹) divided by the three-year total N applied (kg N ha⁻¹) for 2022-2024; soybean was excluded (no N fertilizer). Bars are least-squares means from a split-plot linear mixed model with fixed effects of rotation (C, C-Sg, C-Sb, C-W, C-C-W), cover crop (No/Yes), and their interaction, and random effects of block, block×rotation, and block×rotation×plot_pair. Error bars indicate ±1 SE of the LS-means. Within each rotation, cover-crop levels were contrasted with Tukey adjustment; different letters mark significant differences at α = 0.05 (absence of letters indicates no significant difference). All plots were rainfed (no supplemental irrigation).

Chapter 4 - Effect of Crop Rotation and Nitrogen Fertilization

Strategies on Productivity and Soil Properties

Abstract

Improving nitrogen use efficiency (NUE) in wheat-based systems is critical to enhance productivity while reducing environmental losses. The objective of this study was to evaluate the effects of crop rotation and nitrogen management strategies in wheat-based systems on grain yield, NUE, water use efficiency (WUE), and economic return. Four treatments were evaluated from 2019 to 2024 in northeastern Kansas, USA, representing combinations of three crop rotations and two nitrogen management strategies on rainfed conditions. The Normal strategy consisted of a single broadcast application of urea-ammonium nitrate (UAN), whereas the Progressive strategy incorporated “4R” principles, including split applications, improved placement, and the use of inhibitors with rates adjusted to seasonal conditions. Across the 2020 to 2024 period, average annual glucose equivalent yield did not differ among treatments, indicating that neither crop rotation intensity nor N management strategy affected system level productivity. Nitrogen use efficiency varied among treatments, with the continuous wheat system showing the highest NUE and intensive systems the lowest, while precipitation use efficiency followed the opposite pattern, with higher values under intensive rotations. Direct comparisons between Normal and Progressive strategies within the same rotation showed no significant differences in yield, NUE, or precipitation use efficiency. However, economic analysis revealed that Progressive N management consistently resulted in higher partial net returns than conventional management. These results indicate that, although improvements in nitrogen use may be modest from an agronomic perspective, they can enhance economic resilience without compromising productivity.

Introduction

Wheat-based cropping systems are a foundation of dryland agriculture in the U.S. Great Plains, supporting regional economy and global food supply. However, maintaining their productivity while minimizing environmental losses remains a major challenge, particularly regarding nitrogen (N) management. Nitrogen fertilization is among the most influential inputs affecting wheat yield, grain protein, and overall system profitability. Yet, inefficient N use contributes to environmental risks through nitrate leaching, runoff, volatilization, and denitrification, while inadequate rates can limit yield potential (Raun and Johnson, 1999; Ladha et al., 2005). These challenges highlight the need for nitrogen management approaches that better synchronize N supply with crop demand across variable dryland conditions, thereby improving efficiency while reducing reliance on external inputs. Achieving a balance between productivity and environmental stewardship, therefore, requires refining N management practices within realistic, field-scale systems. Multi-year experiments comparing contrasting N strategies and crop rotations can provide valuable insight into how management decisions influence Nitrogen Use Efficiency (NUE), productivity stability, and system sustainability (Cassman et al., 2002; Snyder et al., 2009).

Crop rotation diversification plays a central role in improving nitrogen dynamics and overall system sustainability in wheat-based systems. Integrating crops with contrasting functional traits, such as legumes and cover crops, can enhance nitrogen cycling, soil fertility, and resource-use efficiency (Drinkwater et al., 1998; Obour et al., 2021). Legumes like cowpea and soybean contribute biologically fixed N that supplements soil N availability for subsequent wheat crops, reducing fertilizer requirements and improving nitrogen use efficiency (Watson et al., 2002; Ciampitti and Salvagiotti, 2018). Including additional crops such as sorghum, corn, or

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triticale increases rotational diversity, and represents a form of rotational intensification that can provide opportunities for residue management and cover crop benefits that support soil structure and reduce erosion risks (Ayalew et al., 2018; Obour et al., 2021; Blanco-Canqui et al., 2022; Simon et al., 2022; Schnarr et al., 2022). In the central Great Plains, soybean has been widely adopted in wheat-based rotations and double-crop systems, improving rotational productivity and net returns relative to continuous wheat, when climatic conditions are favorable (Kelley, 2003; Santos Hansel et al., 2019). Similarly, cowpea has shown potential as a short-season or grazeable legume option in wheat-sorghum rotations, contributing additional N inputs and enhancing system resilience under dryland conditions (Horn et al., 2020). Consequently, comparing wheat-based rotations that differ in crop diversity and nitrogen management helps identify management combinations that sustain productivity and improve resource use efficiency under the variable conditions of the Great Plains.

Despite extensive research on nitrogen management and NUE in wheat and other cereals, most studies have focused on fertilizer rate, tillage, or individual agronomic practices rather than on whole-rotation, system-level responses. Meta analyses and long-term experiments have demonstrated that practices such as conservation tillage, cover crops, manure application, and moderate N rates can improve winter wheat yield and NUE under dryland conditions, but these studies generally consider relatively simple cropping systems or monoculture wheat and do not explicitly compare contrasting N strategies within diversified wheat-based rotations. Likewise, long-term rotational studies and legume-based systems consistently show that including legumes in rotation can enhance subsequent wheat yield and N uptake, yet they often emphasize yield or N balances in specific crop sequences rather than integrating yield, NUE, and inter-annual stability across multiple crops and N management strategies. As a result, there is still relatively

limited information on how different combinations of rotational diversity and N management perform in dryland wheat-based systems of the central Great Plains, particularly when evaluated over multiple years and with metrics that capture both productivity and system-level N efficiency.

This chapter examines how four wheat-based rotations differing in crop diversity and N management influence key agronomic and efficiency outcomes under dryland conditions. Specifically, the study evaluates grain yield and its inter-annual stability across rotations, quantifies NUE as an indicator of fertilizer utilization, and assesses broader system performance by considering the contribution of rotational crops, including legumes, to total productivity. By integrating these metrics, the chapter extends the system-level perspective developed in Chapters 2 and 3 to the context of wheat-based rotations, providing insight into how rotational intensity and N management interact to shape productivity and resource use efficiency in semi-arid environments.

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Materials and Methods

This study evaluated four wheat-based rotations that differed in both crop diversity and nitrogen (N) management strategy. The Baseline Normal (baseN) system represented a conventional wheat-fallow rotation fertilized using a standard fixed-rate approach. The Adaptive Grain Progressive (adgrP) rotation incorporated greater crop diversity through legumes such as cowpea and soybean, which may contribute with biologically fixed N and reduce fertilizer dependence for subsequent wheat crops. The Intensive Normal (intN) and Intensive Progressive (intP) systems followed the same diversified cereal-legume rotation but differed in their N management: intN used a conventional fixed-rate program, whereas intP employed a more

responsive strategy designed to better align N availability with crop demand across seasons. Together, these four treatments span a gradient from a traditional wheat-fallow system with uniform fertilization toward more diversified and potentially N-efficient rotations, enabling evaluation of how rotational intensity and N strategy interact to influence system performance under dryland conditions.

Experimental site

From October 2019 to October 2023 a field experiment was conducted at the Kansas State University Ashland Bottoms Experiment Research Station (39.124945; -96.635112) located near Manhattan, Kansas. The annual precipitation average for the location was 855 mm and the temperature 13.8 °C (Figure 4.1). The crop rotations were under a rainfed, no-tillage system. Previously, the rotation: sorghum-soybean-wheat was planted under conventional tillage. The soil in the site location was classified as Wymore series, fine mesic Aquertic Argiudoll, with silty clay loam texture (Baillie, 2001).

Experimental design and treatments

The field experiment was established as a randomized complete block design with four replications. Four treatments were included: Baseline Normal (baseN), Adaptative Grain Progressive (adgrP), Intensive Normal (intN), and Intensive Progressive (intP); each corresponding to one of three distinct crop rotations (Figure 4.2) and two nitrogen management strategies: the “Normal” strategy followed a conventional fixed-rate program, applying 100 kg N ha⁻¹ as urea-ammonium nitrate (UAN) solution, broadcast at Feekes 3 in wheat and at planting for corn and sorghum. In contrast, the “Progressive” strategy incorporated adaptive components

intended to better synchronize N supply with crop demand. This approach included split applications (Feekes 4 and 7 in wheat; planting and V₆ in corn and sorghum), the use of urease and nitrification inhibitors, and in-season rate adjustments guided by yield potential and environmental conditions. In the Progressive treatments, Nitrogen was applied through stream bars rather than broadcast to reduce volatilization risk and improve placement efficiency, and the annual rates ranged from 85 to 110 kg N ha⁻¹ depending on crop and season (Table 4.1). Together, these treatments reflect a management gradient from conventional, uniform N application toward more responsive, efficiency-oriented fertilization tailored to dynamic field conditions. Precipitation and temperature information for the site were obtained from Kansas Mesonet station in Ashland Bottoms (2025).

Crop management

The experiment was conducted under rainfed conditions (no irrigation) and managed using a continuous no-till system throughout the study period. In 2019, winter wheat was planted on October 24 across all treatments; in subsequent years, wheat in the Baseline Normal rotation was sown at the optimal planting window (mid-October), whereas wheat and triticale in the remaining rotations were planted later, around mid-November. Summer crops following winter fallow or triticale were established early in the season (mid-May), while summer crops planted after winter wheat (cowpea, grain sorghum, and corn) were sown later (early July), immediately after wheat harvest. Winter wheat and triticale were seeded in 0.19-m row spacing using a 9-row Great Plains 606® no-till drill (Great Plains Manufacturing, Salina, KS, USA). Forage soybean, grain soybean, corn, sorghum, and cowpea were planted in 0.76-m row spacing with a 2-row John Deere 7000® planter (John Deere, Moline, IA, USA). Forage soybean was mowed at the

R3 growth stage (beginning pod), and all biomass was removed. Triticale grown as a cover crop was chemically terminated at the boot stage using glyphosate approximately two weeks prior to planting the following summer crop.

Diammonium phosphate (DAP; 18-46-0) was applied in-furrow at winter crop planting at a rate of 55 kg ha⁻¹, and nitrogen fertilization for both winter and summer crops followed the treatment-specific programs detailed in Table 4.1. Weed management consisted of pre-emergence and post-emergence herbicide applications, supplemented by hand weeding when necessary, and herbicide mixtures were also used during fallow periods to suppress weed growth. No insecticides or fungicides were applied during the study.

Measurements

Soil sampling was performed in 2022 and 2023 at three depth intervals (0-15, 15-30, and 30-60 cm) using a 2.5 cm diameter hand probe. For the 0-15 and 15-30 cm layers, twelve subsamples were collected within each plot and composited, whereas for the 30-60 cm layer, six to eight subsamples (depending on soil conditions) were combined to generate a single representative sample per plot and depth. Samples were taken in May and June to capture changes in soil properties during the growing season. All soil samples were air-dried at 40 °C, ground, passed through a 2 mm sieve, and stored in plastic containers prior to laboratory analysis.

Inorganic nitrogen (NO₃⁻ and NH₄⁺) was extracted with 2 M KCl and quantified following the procedure of Mulvaney (1996). Soil chloride (Cl⁻) was extracted with a calcium nitrate solution and determined colorimetrically using the Mercury II thiocyanate method (Gelderman et al., 1980), and sulfate-sulfur (SO₄-S) was extracted with monocalcium phosphate

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and quantified turbidimetrically on a flow analyzer (Combs et al., 1998), following the procedures described in the Recommended Chemical Soil Test Procedures for the North Central Region (Gelderman et al., 1980).

Soil moisture was measured using the gravimetric method described by Briggs and McLane (1910). A fresh soil sample was weighed to record its initial wet mass, after which it was dried in an oven at 105 °C (221 °F) for 24 hours. The sample was weighed again to obtain its dry mass. Gravimetric moisture content was calculated as the difference between wet and dry weights, divided by dry weight and expressed as a percentage, using the equation:

$$\text{Moisture Content}(\%) = \frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Dry Weight}} \times 100$$

Winter wheat grain yield was measured by harvesting the center of each plot (18.5 m²) with a small-plot, self-propelled Massey Ferguson XP8 combine (Massey Ferguson Corp, Duluth, GA), except in 2023, when it was harvested manually (2 m²). For summer crops, grain yield was determined by hand-harvesting the center of each plot (1 m² for soybeans and cowpea and 7 m² for sorghum and corn), followed by threshing the pods or shelling the ears using a stationary machine.

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Calculations

Glucose equivalent yield (kg GE/ha) was obtained by multiplying crop yield by a crop-specific glucose conversion factor, which represents the amount of glucose required to produce one kilogram of grain. The factors used were 1.46 for soybeans, 1.39 for corn, 1.36 for sorghum, and 1.27 for wheat (De Vries et al., 1983).

$$\text{Glucose equivalent (kg ha}^{-1}\text{)} = \text{Yield (kg ha}^{-1}\text{)} * \text{Glucose Factor}$$

Precipitation use efficiency (PUE) was calculated as the ratio of glucose-equivalent yield (kg GE ha⁻¹) to total precipitation (mm), reflecting the efficiency with which rainfall was converted into crop production under rainfed conditions:

$$PUE = \frac{Yield (kg GE ha^{-1})}{Total Precipitation (mm)}$$

Nitrogen use efficiency (NUE) was estimated as the partial factor productivity of nitrogen, representing grain output per unit of nitrogen applied. NUE was calculated by dividing glucose-equivalent yield (kg GE/ha) by the amount of nitrogen applied (kg N/ha) in each treatment:

$$NUE = \frac{Yield (kg GE ha^{-1})}{N applied (kg N ha^{-1})}$$

This metric provides an indicator of the efficiency and sustainability of nitrogen fertilization practices across treatments (Dobermann, 2007).

Statistical analysis

All statistical analyses were performed using R version 4.x.x (R Core Team, 2024) within the RStudio integrated development environment (RStudio version 2024.09.1, Posit PBC). Analysis of variance (ANOVA) was conducted to evaluate the effects of treatments on the response variables. Linear mixed-effects models (lmer, package lme4) were used, and model assumptions (normality of residuals and homogeneity of variances) were verified using diagnostic plots and the performance and car packages. When significant treatment effects were detected ($p < 0.05$), means were compared using Tukey's Honestly Significant Difference (HSD) test with the emmeans package.

All graphs and summary tables were also generated in R using ggplot2 and dplyr.

Commented [KR25]: Shouldn't this be rotational precip? What about precip during fallow?

Economic analysis

A partial net return analysis was conducted to compare the economic performance of the two nitrogen (N) management strategies evaluated in this study. The analysis focused exclusively on costs that differed between treatments, following a partial budgeting approach. Specifically, the two strategies differed in the number and complexity of N applications: the conventional treatment involved a single application of urea-ammonium nitrate (UAN), whereas the alternative treatment included split N applications combined with the use of urease and nitrification inhibitors. Costs associated with nitrogen fertilizer, inhibitors, and application were included, while all other production costs were assumed to be equal across treatments and therefore excluded from the analysis. Gross income was calculated as the product of crop yield and grain price, and partial net return was estimated as gross income minus treatment-specific N costs. Grain and input prices were obtained from enterprise budgets developed by the Department of Agricultural Economics at Kansas State University for 2024, using both high- and low-price scenarios to account for market variability.

Commented [KR26]: Didn't they also differ in application method/placement?

Commented [PG27R26]: Yes but that doesn't make a difference in cost (just switch nozzles)

Results and Discussion

Average annual glucose-equivalent yield from 2020 to 2023 did not differ significantly among the four treatments evaluated (Figure 4.3). Estimated marginal means ranged from approximately 4.3 to 5.2 Mg GE ha⁻¹, with the Intensive Normal (intN) treatment showing the highest numerical yield and the Adaptive Grain Progressive (adgrP) treatment the lowest. However, Tukey-adjusted pairwise comparisons indicated no statistically significant differences among treatments ($\alpha = 0.05$), indicating that differences in crop rotation intensity and nitrogen

(N) management strategy did not translate into detectable differences in system-level productivity under the dryland conditions of this study.

The absence of significant differences in glucose-equivalent yield among treatments suggests that increasing cropping intensity and rotational diversity did not result in a measurable gain in total system productivity. This is particularly relevant because some treatments included double-crop phases, where two harvested crops contributed to annual output, whereas continuous wheat relied on a simpler cropping structure. Under these conditions, the diversified systems might have been expected to equal or exceed continuous wheat in cumulative productivity; however, that advantage was not statistically realized. Expressing yield as glucose equivalents allows comparison across rotations that differ in crop composition and harvest frequency, providing a system-level perspective that emphasizes resource-use efficiency rather than yield maximization alone. Similar patterns have been reported in other dryland studies in the Great Plains, where diversified rotations often maintain, but do not exceed, wheat-fallow yields.

In contrast to yield, average annual nitrogen use efficiency (NUE) differed among treatments when averaged across the 2020-2023 period (Figure 4.4). The baseN treatment exhibited the highest NUE, followed by adgrP, whereas the Intensive Normal (intN) treatment showed the lowest NUE; the Intensive Progressive (intP) treatment had intermediate values. These differences occurred even though glucose-equivalent yield did not differ significantly among treatments. The lower NUE observed in intN and intP was likely associated with their greater overall N inputs, since these systems included additional crop phases and therefore received more fertilizer across the rotation. However, the added N did not translate into proportionally greater system productivity, since yields of the summer double-crop species, planted after wheat, were generally low, which further reduced the efficiency with which applied

N was converted into harvested output. This highlights a key trade-off in dryland systems, where increasing cropping intensity may sustain productivity but often at the expense of nitrogen efficiency.

The annual NUE patterns suggest that both crop sequence and N management strategy influenced how efficiently applied N was converted into system productivity (Figure 4.5). Across years, the largest differences generally reflected the crops present in each rotation during that season. For example, in 2020 the lower NUE observed in intN and intP was likely related to the inclusion of low-yielding summer double-crop phases, which received additional N inputs but did not produce enough glucose-equivalent yield to offset those applications. In contrast, baseN and adgrP had higher NUE because they relied more heavily on wheat phases, which generally produced greater productivity per unit of applied N.

Differences between intN and intP are especially informative because both treatments followed the same rotation but differed in N management strategy. The progressive approach in intP adjusted N rates annually based on predicted yield potential and environmental conditions, whereas intN followed a more fixed-rate program. As a result, intP often achieved equal or greater NUE than intN, particularly in 2020 and 2022, suggesting that more adaptive N management improved fertilizer use efficiency under variable growing conditions. However, this advantage was not consistent across all years, indicating that the benefits of the progressive strategy depended on seasonal conditions and crop performance.

By 2023, only baseN and adgrP were present because the intensive systems were in soybean or fallow phases and therefore were not included in the NUE comparison. The lack of significant difference between baseN and adgrP that year suggests that when both systems were

dominated by wheat-based phases, their efficiency of N conversion was relatively similar despite differences in management strategy.

Precipitation use efficiency (PUE) did not differ significantly among treatments when averaged across the study period (Figure 4.6), mirroring the response observed for glucose-equivalent yield. Because all treatments received the same precipitation, differences in PUE largely reflected differences in system productivity rather than water supply. Numerically, intN and intP showed the highest PUE values, whereas baseN and adgrP had slightly lower values; however, these differences were not statistically significant.

The absence of treatment effects suggests that the more intensive rotations were not able to convert available precipitation into significantly greater system productivity than the less intensive wheat-based systems. Although the intensive systems included additional crop phases and, in some cases, more than one harvested crop within the same year, this added cropping intensity did not result in a measurable increase in precipitation use efficiency. Thus, under the environmental conditions of this study, increasing rotational complexity and cropping frequency did not substantially improve the efficiency with which precipitation was converted into harvested output.

Average wheat yield differed among treatments (Figure 4.7). The baseN treatment produced the highest wheat yield, whereas adgrP had the lowest. The intN and intP treatments were intermediate and did not differ significantly from either baseN or adgrP. These results suggest that continuous wheat and the simpler wheat-based system tended to favor greater wheat productivity than the more diversified systems.

The lower wheat yield observed in adgrP may reflect the inclusion of a wheat double-crop legume phase and shorter fallow periods, which could reduce soil water availability for the

subsequent wheat crop under dryland conditions. In contrast, the greater wheat yield in baseN was likely associated with the continuous wheat system having fewer competing crop phases and potentially greater residual soil water at planting. The intermediate wheat yields in intN and intP suggest that the more intensive wheat-double crop systems with corn or sorghum followed by soybeans did not strongly penalize wheat productivity, despite their greater overall cropping intensity.

Direct comparison of intN and intP, which share the same crop rotation but differ in N management, showed no statistically significant differences in system yield, wheat yield, NUE, or PUE (Figure 4.9). Although intP exhibited numerically higher NUE and slightly lower PUE, these differences were not significant, indicating that progressive N management did not consistently improve agronomic or efficiency outcomes under the prevailing dryland conditions.

Economic analysis further contextualized these agronomic results. Partial net return differed between N management strategies depending on crop type and price scenario (Figure 4.10). Under both high- and low-price scenarios, intP consistently resulted in higher partial net returns than intN for both wheat and corn. Differences were modest under high prices but more pronounced under low-price conditions, particularly for wheat. Although intP incurred higher N management costs, these were offset by comparable yields and, in some cases, improved nitrogen efficiency, suggesting greater economic resilience under unfavorable market conditions.

Finally, soil nutrient analyses showed no significant differences among treatments for nitrate, ammonium, chloride, or sulfur at any depth (0-15, 15-30, or 30-60 cm) when averaged across 2022 and 2023 (Figures 4.11 and 4.12). The lack of treatment effects suggests that differences in cropping intensity and N management influenced crop uptake and system-level efficiency rather than short-term changes in residual soil nutrient pools.

Conclusion

The results of this study indicate that increasing crop diversity and cropping intensity in dryland wheat-based systems did not improve system-level productivity. Although the more intensive rotations included additional crop phases and, in some cases, double-crop sequences, they did not produce greater glucose-equivalent yield than the less intensive wheat-based systems. Under the conditions of this study, the expected productivity advantage of greater cropping intensity was not realized.

The study also highlights an important trade-off between cropping intensity and nitrogen efficiency. More intensive systems required greater N inputs but did not proportionally increase productivity, resulting in lower NUE. In contrast, the less intensive wheat-based systems maintained similar productivity with lower fertilizer inputs and therefore greater nitrogen efficiency. Precipitation use efficiency followed a similar pattern to yield, indicating that additional crop phases did not substantially improve the conversion of rainfall into harvested output.

Overall, the findings of this chapter demonstrate that crop rotation structure and cropping intensity exert a stronger influence on productivity and resource-use efficiency than nitrogen management strategy alone in dryland wheat-based systems. While progressive N management may enhance economic outcomes, long-term sustainability in these systems depends on balancing rotational diversity, nitrogen efficiency, precipitation use, and economic risk under highly variable climatic conditions.

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Tables and Figures

Table 4.1 Nitrogen application rates for the Intensive Normal (intN) and Intensive Progressive (intP) treatments by crop and year.

Year	Crop	Rate (intN)	Rate (intP)
		----- kg ha ⁻¹ -----	
2020	Wheat	100	100
2022	Wheat	100	85
2022	Corn	135	67.5
2024	Wheat	100	110
2024	Corn	135	135

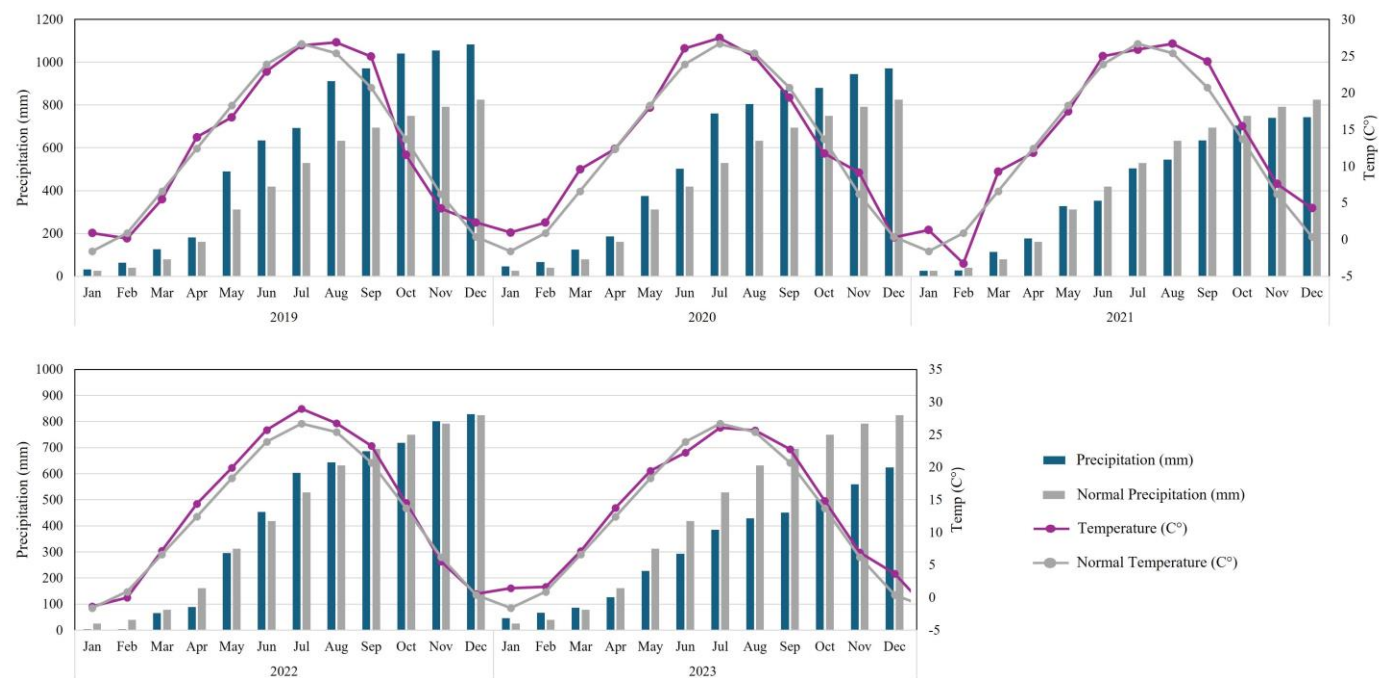


Figure 4.1 Accumulated monthly precipitation (mm) and average monthly temperature from 2019 to 2023 at the experimental station. Dark blue bars represent precipitation, and grey bars the 2019-2023 monthly precipitation normal (Kansas Mesonet, 2024). Purple lines with circles represent average monthly temperature for each year, and gray lines with circles represent the 1991-2020 temperature normal.

	2019	2020		2021		2022		2023	
baseN									
adgrP									
intN /intP									

 **Wheat**

 **Sorghum**

 **Cowpea**

 **Soybean**

 **For. Soybean**

 **Corn**

 **Triticale**

Figure 4.2 Crop rotation sequences for the four treatments evaluated in the experiment from 2019 to 2023: baseN (Baseline), adgrP (Adaptive Grain Progressive), intN (Intensive Normal), and intP (Intensive Progressive). Each row represents one rotation, and icons depict the crop grown in each year of the rotation cycle (left to right). Treatments intN and intP followed the same crop rotation sequence. Shaded cells indicate fallow periods. Rotations consisted of winter wheat , sorghum , cowpea , soybean, forage soybean, corn, and triticale as a cover crop, depending on treatment and year.

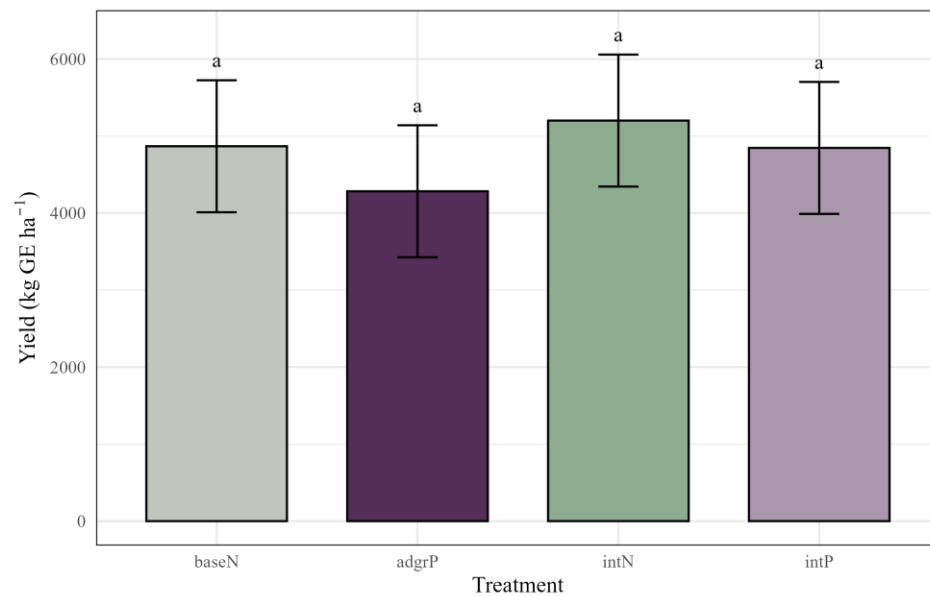


Figure 4.3 Average annual glucose-equivalent yield (kg GE ha⁻¹) from 2020 to 2023 across four treatments: baseN (Baseline), adgrP (Adaptive Grain Progressive), intN (Intensive Normal), and intP (Intensive Progressive). Treatments integrate differences in crop rotation and nitrogen management. Bars represent estimated marginal means obtained from a linear mixed-effects model including treatment as a fixed effect and replication and year as random intercepts. Error bars indicate standard errors. There were no statistically significant differences among treatments based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$).

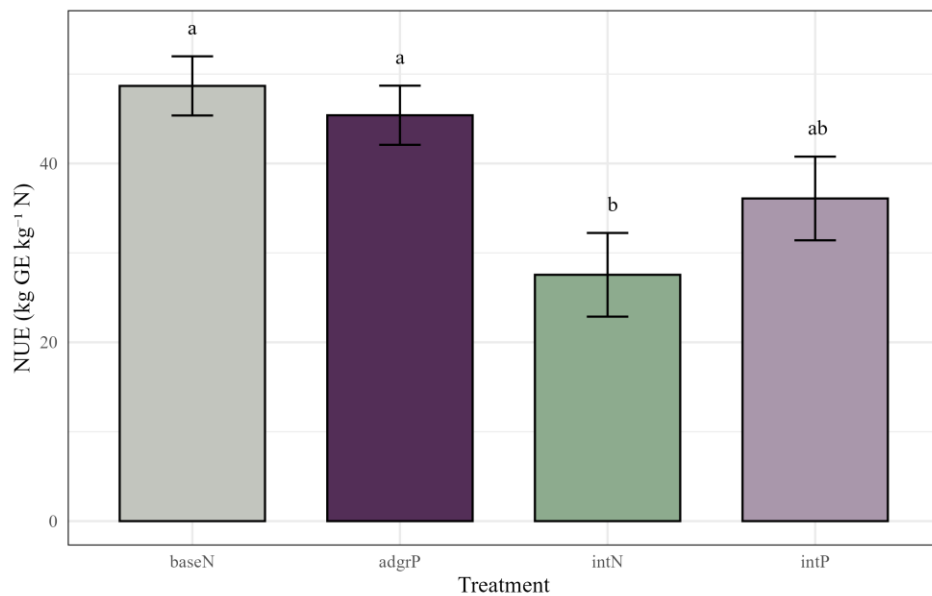


Figure 4.4 Average annual nitrogen use efficiency (NUE; kg GE kg⁻¹ N) from 2020 to 2023 across four treatments: baseN (Baseline), adgrP (Adaptive Grain Progressive), intN (Intensive Normal), and intP (Intensive Progressive). Treatments integrate differences in crop rotation and nitrogen management. Bars represent estimated marginal means obtained from a linear mixed effects model including treatment as a fixed effect and replication as random intercept. Error bars indicate standard errors. Different letters above bars denote statistically significant differences among treatments based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$).

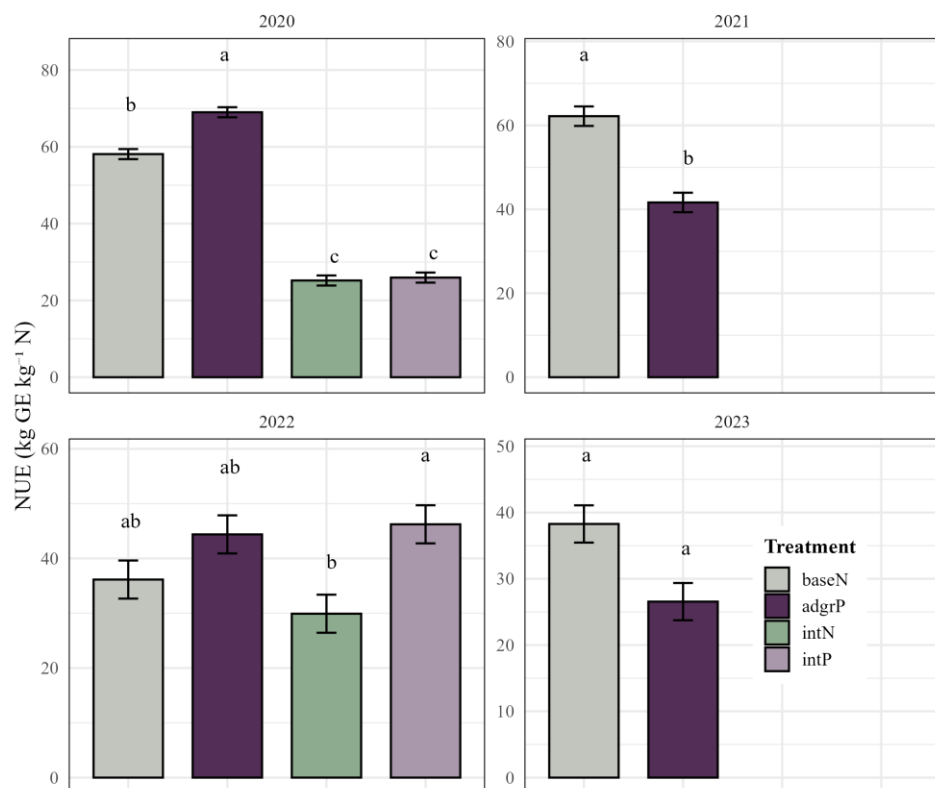


Figure 4.5 Annual nitrogen use efficiency (NUE; kg GE kg⁻¹ N) from 2020 to 2023 across four treatments: baseN (Baseline), adgrP (Adaptive Grain Progressive), intN (Intensive Normal), and intP (Intensive Progressive). Treatments integrate differences in crop rotation and nitrogen management. Bars represent estimated marginal means obtained from linear mixed effects models including replication as random effect. Error bars indicate standard errors. Different letters above bars denote statistically significant differences among treatments within each year based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$, Kenward-Roger method for degrees of freedom).

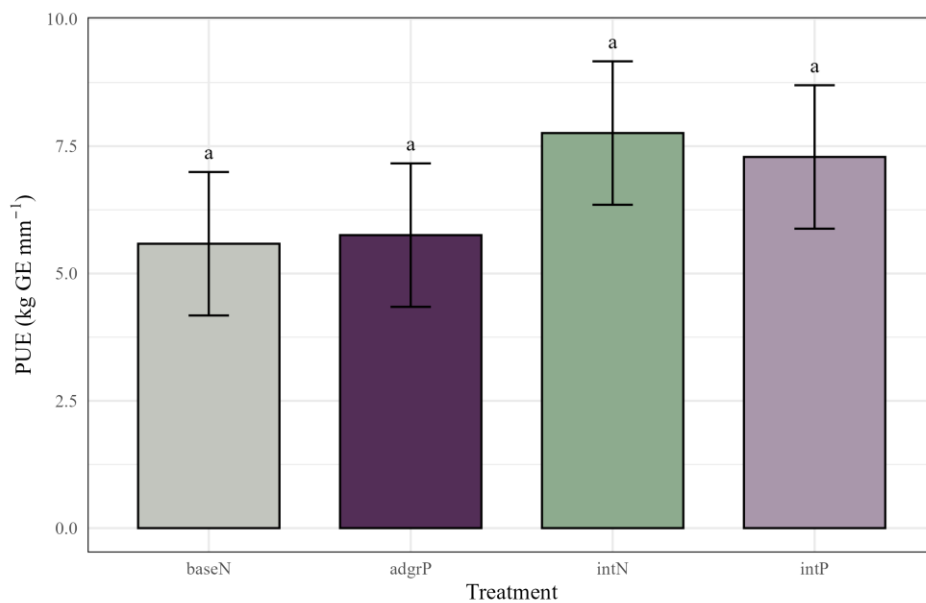


Figure 4.6 Average annual water use efficiency (PUE; kg GE mm⁻¹) from 2020 to 2023 across the four treatments: baseN (Baseline), adgrP (Adaptive Grain Progressive), intN (Intensive Normal), and intP (Intensive Progressive). Treatments differ in both crop rotation structure and nitrogen management strategy. Bars represent estimated marginal means obtained from a linear mixed effects model including treatment as a fixed effect and replication and year as random intercepts. Error bars correspond to standard errors of the estimates. Different letters above bars denote statistically significant differences among treatments based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$).

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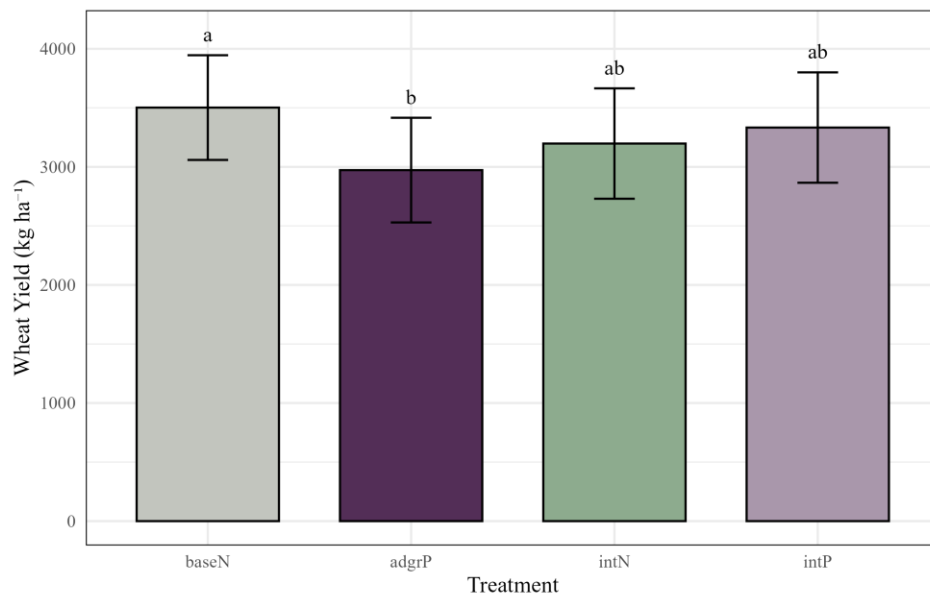


Figure 4.7 Average wheat yield (kg ha^{-1}) from 2020 to 2023 across four treatments: baseN (Baseline), adgrP (Adaptive Grain Progressive), intN (Intensive Normal), and intP (Intensive Progressive). Treatments integrate differences in crop rotation and nitrogen management. Bars represent estimated marginal means obtained from a linear mixed effects model including year and replication as random effects. Error bars indicate standard errors. Different letters above bars denote statistically significant differences among treatments based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$, Kenward-Roger method for degrees of freedom).

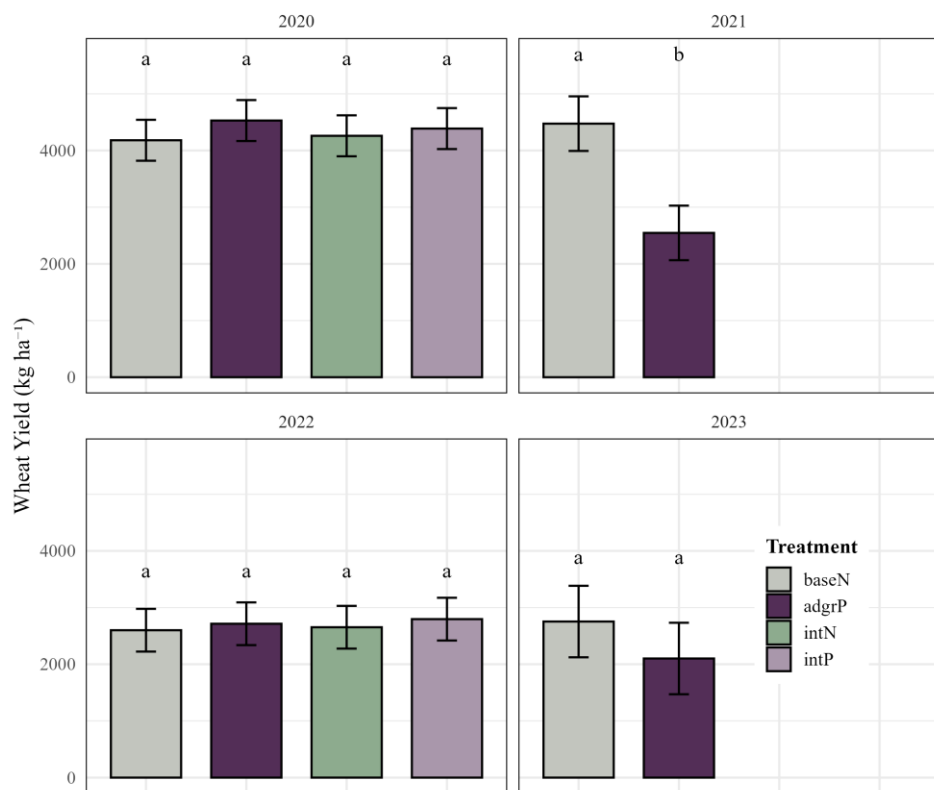


Figure 4.8 Annual wheat yield (kg ha^{-1}) from 2021 to 2023 across four treatments: baseN (Baseline), adgrP (Adaptive Grain Progressive), intN (Intensive Normal), and intP (Intensive Progressive). Treatments integrate differences in crop rotation and nitrogen management. Bars represent estimated marginal means obtained from linear mixed effects models including replication as random effect. Error bars indicate standard errors. Different letters above bars denote statistically significant differences among treatments within each year based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$, Kenward-Roger method for degrees of freedom).

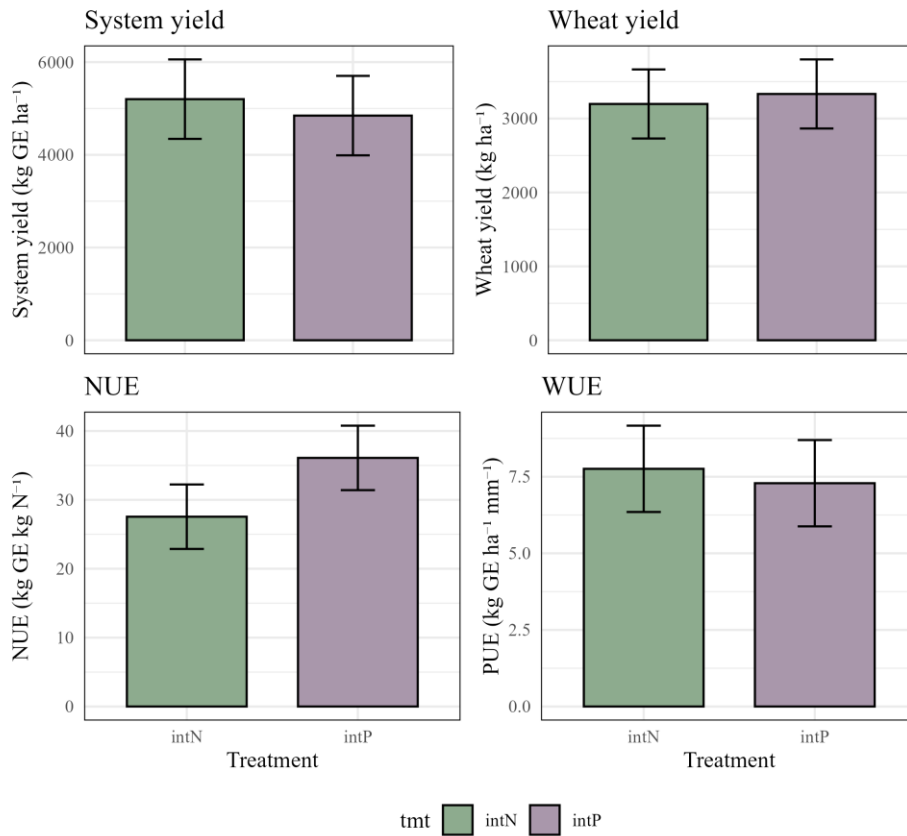


Figure 4.9 Comparison of productivity and resource use efficiencies between the Intensive Normal (intN) and Intensive Progressive (intP) treatments, which share the same crop rotation sequence but differ in nitrogen management strategy. The four panels display: system yield expressed in glucose-equivalent units (kg GE ha⁻¹) in the upper-left panel; wheat yield (kg ha⁻¹) in the upper-right panel; nitrogen use efficiency (NUE; kg GE kg⁻¹ N) in the lower-left panel; and water use efficiency (PUE; kg GE mm⁻¹) in the lower-right panel. Bars represent estimated marginal means obtained from linear mixed effects models including treatment as a fixed effect and replication and year (except for NUE) as random intercepts. Error bars indicate standard errors of the estimates. No statistically significant differences were detected between intN and intP for any of the evaluated variables based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$).

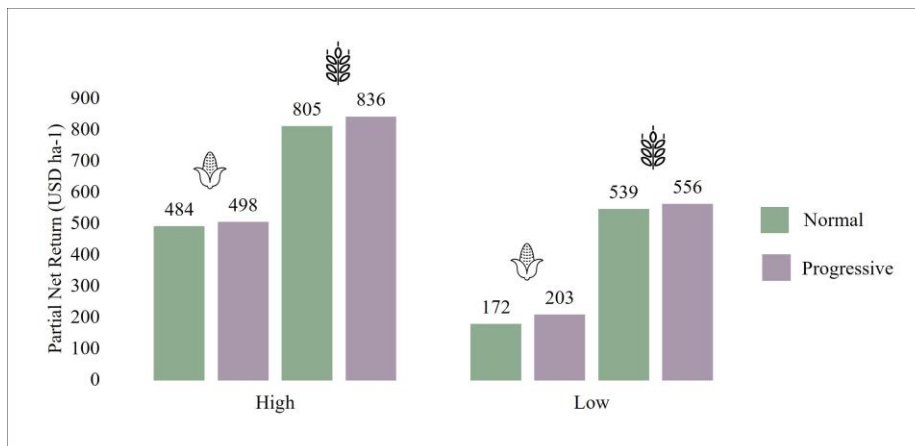


Figure 4.10 Partial net return (USD ha⁻¹) for the Intensive Normal (intN) and Intensive Progressive (intP) treatments under two price scenarios: High and Low, for corn and wheat. Icons above each panel indicate the corresponding crop. Bars represent the partial net return calculated as gross revenue minus nitrogen fertilizer cost for each treatment-crop-price combination. High and Low scenarios were defined based on historical commodity price ranges for the region. Values displayed above bars correspond to the treatment means.

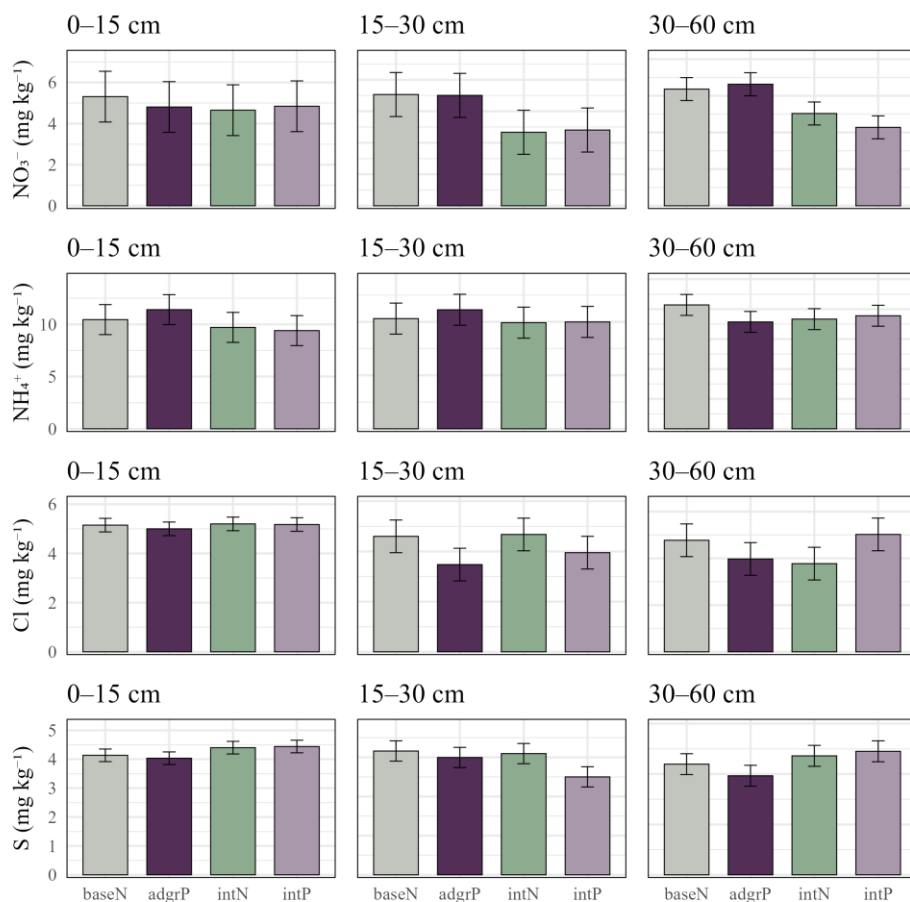


Figure 4.11 Soil concentrations of nitrate (NO₃⁻-N), ammonium (NH₄⁺-N), chloride (Cl⁻), and sulfur (S) across four treatments: baseN (Baseline), adgrP (Adaptive Grain Progressive), intN (Intensive Normal), and intP (Intensive Progressive), at three soil depths: 0-15 cm, 15-30 cm, and 30-60 cm. Values represent two-year averages (2022 and 2023). Bars represent estimated marginal means obtained from linear mixed effects models fitted separately for each nutrient and depth, with treatment as a fixed effect and replication as a random intercept. Error bars show standard errors of the estimates. No statistically significant differences among treatments were detected for any nutrient-depth combination based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$).

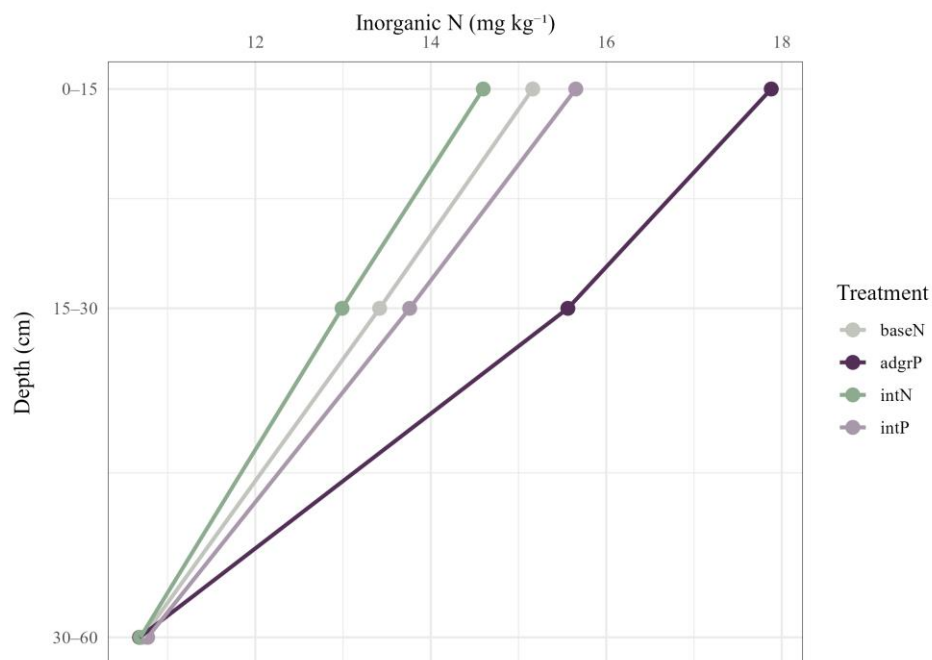


Figure 4.12 Inorganic nitrogen (NO_3^- -N + NH_4^+ -N) concentrations across four treatments: baseN (Baseline), adgrP (Adaptive Grain Progressive), intN (Intensive Normal), and intP (Intensive Progressive), at three soil depths (0-15, 15-30, and 30-60 cm). Values represent two-year averages (2022 and 2023). Lines connect depth-specific estimated marginal means obtained from a linear mixed-effects model including treatment, depth, and their interaction as fixed effects; replication, plot, and plot-specific depth slopes were included as random effects. Error bars indicate standard errors of the estimates. No statistically significant treatment differences were detected within any depth based on Tukey-adjusted pairwise comparisons ($\alpha = 0.05$).

Chapter 5 - General conclusions

This thesis evaluated how crop rotation design, cover crop integration, and nitrogen management influence productivity, resource-use efficiency, soil properties, and economic performance in water-limited environments of the Central Great Plains. By combining long-term experiments under limited irrigation with a complementary multi-year rainfed study, this work provides a systems-level assessment of how management decisions interact with water availability to shape agronomic and sustainability outcomes.

Across corn-based systems under limited irrigation, crop rotation emerged as a primary driver of system performance. Results demonstrated that no single rotation optimized all dimensions of productivity, efficiency, and profitability. Continuous corn maximized glucose-equivalent yield, water-use efficiency, and economic return, but at the expense of lower nitrogen use efficiency due to higher fertilizer inputs. In contrast, rotations incorporating legumes improved NUE but often at the expense of productivity and water-use efficiency. More diversified rotations, particularly corn-sorghum and corn-corn-wheat, consistently offered balanced trade-offs, sustaining high productivity and profitability while maintaining moderate resource-use efficiency. These findings highlight that rotation selection under limited irrigation should be guided by producer objectives and risk tolerance rather than by yield alone.

Soil responses to long-term rotation management were more subtle than crop productivity responses. After seven years, crop rotation did not significantly alter total soil carbon or nitrogen stocks to 120 cm, indicating that detectable changes in these pools may require longer time horizons under limited irrigation. Instead, rotation effects were expressed primarily in surface soil properties, particularly pH and mineral nitrogen distribution, reflecting cumulative nitrogen management history rather than fundamental shifts in soil carbon or nitrogen storage. These

results emphasize the importance of monitoring surface soil conditions, especially acidification in corn-intensive systems.

The introduction of cover crops within the long-term, limited-irrigation experiment demonstrated that, when managed properly, cover crops can be integrated without short-term penalties to system-level productivity, water-use efficiency, or nitrogen-use efficiency. Although crop-specific responses occasionally occurred, these effects did not propagate to the rotation scale over the three-year evaluation period. This finding supports the feasibility of cover crop adoption in water-limited systems.

In rainfed wheat-based systems, water availability exerted an even stronger control over system outcomes. Increasing rotational diversity and cropping intensity maintained system-level productivity comparable to a conventional wheat-fallow system, demonstrating that diversified rotations can sustain production under dryland conditions. However, nitrogen use efficiency declined with increasing intensity and N input, while precipitation use efficiency improved, highlighting a fundamental trade-off between nitrogen efficiency and water capture in rainfed systems. Comparisons of nitrogen management strategies showed that progressive N approaches did not consistently improve yield or efficiency metrics relative to conventional management, reflecting the dominant influence of precipitation variability on crop response. Nonetheless, modest improvements in nitrogen efficiency translated into higher partial net returns, particularly under unfavorable price scenarios, indicating potential gains in economic resilience.

Collectively, the results of this thesis demonstrate that sustainable intensification in the Central Great Plains cannot be achieved through single management interventions. Instead, long-term sustainability depends on aligning crop rotation design, nitrogen management, and cover crop integration with prevailing water constraints. While intensified systems can maintain

productivity, their performance is governed by trade-offs among yield, water-use efficiency, nitrogen-use efficiency, and economic risk. Diversified rotations consistently emerged as a robust strategy for balancing these competing objectives under both limited irrigation and rainfed conditions.

This work reinforces the importance of systems-based evaluation for guiding management decisions in semi-arid agriculture. Long-term experiments remain essential for capturing cumulative and legacy effects, while integrative metrics are critical for revealing trade-offs that are not apparent when productivity alone is considered. As water scarcity and climate variability intensify, such approaches will be increasingly necessary to support resilient, efficient, and economically viable cropping systems in the Central Great Plains.

Appendix A - Crop-Specific Management by Year and Rotation

Table A.1 Crop-specific management for each year and rotation, organized by crop, including tillage system, cultivar/hybrid, planting density (seeds ha⁻¹), and planting and harvest dates. “NA” in Harvest Date indicates that the date was not recorded.

Rotation	Year	Tillage	Product	Trait	Planting Date	Harvest Date	Density
							×10 ⁴ seeds ha ⁻¹
----- Corn -----							
C	2015	Strip-Till	DKC51-19RIB	DGVT3PRIB	12-May	26-Oct	5.93
C	2016	Strip-Till	DKC51-19RIB	DGVT3PRIB	7-May	20-Oct	5.93
C	2017	Strip-Till	DKC51-19RIB	DGVT3PRIB	26-May	25-Oct	5.93
C	2018	Strip-Till	DKC51-19RIB	DGVT3PRIB	17-May	25-Oct	5.93
C	2019	No-Till	DKC51-91RIB	SSTXRIB	6-Jun	12-Nov	5.93
C	2020	Strip-Till	DKC51-91RIB	SSTXRIB	9-May	NA	5.93
C	2021	No-Till	DKC51-91RIB	SSTXRIB	6-May	11-Oct	5.93
C	2022	No-Till	DKC51-91RIB	DGVT2PRIB	10-May	1-Nov	5.93
C	2023	No-Till	DKC101-35RIB	VT2PRIB	30-May	18-Oct	5.93
C - W	2015	Strip-Till	DKC51-19RIB	DGVT3PRIB	14-May	26-Oct	5.93
C - W	2016	Strip-Till	DKC51-19RIB	DGVT3PRIB	7-May	20-Oct	5.93
C - W	2017	Strip-Till	DKC51-19RIB	DGVT3PRIB	26-May	25-Oct	5.93
C - W	2018	Strip-Till	DKC51-19RIB	DGVT3PRIB	17-May	25-Oct	5.93
C - W	2019	No-Till	DKC51-20RIB	DGVT2PRIB	6-Jun	12-Nov	5.93
C - W	2020	Strip-Till	01G449	DGVT2PRIB	9-May	NA	5.93
C - W	2021	No-Till	DKC51-20RIB	DGVT2PRIB	6-May	11-Oct	5.93
C - W	2022	No-Till	DKC51-20RIB	DGVT2PRIB	10-May	1-Nov	5.93
C - W	2023	No-Till	DKC51-20RIB	DGVT2PRIB	30-May	18-Oct	5.93
C - Sb	2015	Strip-Till	DKC51-19RIB	DGVT3PRIB	14-May	26-Oct	5.93
C - Sb	2016	Strip-Till	DKC51-19RIB	DGVT3PRIB	7-May	20-Oct	5.93
C - Sb	2017	Strip-Till	DKC51-19RIB	DGVT3PRIB	26-May	25-Oct	5.93

C - Sb	2018	Strip-Till	DKC51-19RIB	DGVT3PRIB	17-May	25-Oct	5.93
C - Sb	2019	No-Till	DKC51-20RIB	DGVT2PRIB	6-Jun	12-Nov	5.93
C - Sb	2020	Strip-Till	01G449	DGVT2PRIB	9-May	NA	5.93
C - Sb	2021	No-Till	DKC51-20RIB	DGVT2PRIB	6-May	11-Oct	5.93
C - Sb	2022	No-Till	DKC51-20RIB	DGVT2PRIB	10-May	4-Nov	5.93
C - Sb	2023	No-Till	DKC51-20RIB	DGVT2PRIB	30-May	18-Oct	5.93
C - C - W	2015	Strip-Till	DKC51-19RIB	DGVT3PRIB	14-May	26-Oct	5.93
C - C - W	2015	Strip-Till	DKC61-55RIB	DGVT2PRIB	18-May	26-Oct	6.42
C - C - W	2016	Strip-Till	DKC51-19RIB	DGVT3PRIB	7-May	20-Oct	5.93
C - C - W	2016	Strip-Till	DKC61-55RIB	DGVT2PRIB	7-May	20-Oct	6.42
C - C - W	2017	Strip-Till	DKC51-19RIB	DGVT3PRIB	26-May	25-Oct	5.93
C - C - W	2017	Strip-Till	DKC60-69RIB	DGVT2PRIB	26-May	25-Oct	6.42
C - C - W	2018	Strip-Till	DKC51-19RIB	DGVT3PRIB	17-May	25-Oct	5.93
C - C - W	2018	Strip-Till	DKC61-55RIB	DGVT2PRIB	17-May	25-Oct	6.42
C - C - W	2019	No-Till	DKC51-91RIB	SSTXRIB	6-Jun	24-Oct	5.93
C - C - W	2019	No-Till	DKC61-55RIB	DGVT2PRIB	6-Jun	24-Oct	6.42
C - C - W	2020	Strip-Till	210-79DGVT2PRIB	DGVT2PRIB	9-May	NA	6.42
C - C - W	2020	Strip-Till	DKC51-91RIB	SSTXRIB	9-May	NA	5.93
C - C - W	2021	No-Till	09G219	DGVT2PRIB	6-May	11-Oct	6.42
C - C - W	2021	No-Till	DKC51-91RIB	SSTXRIB	6-May	11-Oct	5.93
C - C - W	2022	No-Till	DKC51-91RIB	DGVT2PRIB	10-May	1-Nov	5.93
C - C - W	2022	No-Till	DKC61-41RIB	VT2PRIB	10-May	1-Nov	6.42
C - C - W	2023	No-Till	210-79DGVT2PRIB	DGVT2PRIB	30-May	18-Oct	6.42
C - C - W	2023	No-Till	DKC101-35RIB	VT2PRIB	30-May	18-Oct	5.93
C - Sg	2015	Strip-Till	04G234	DGVT2PRIB	18-May	26-Oct	6.42
C - Sg	2016	Strip-Till	04G234	DGVT2PRIB	7-May	20-Oct	6.42
C - Sg	2017	Strip-Till	04G234	DGVT2PRIB	26-May	25-Oct	6.42
C - Sg	2018	Strip-Till	04G234	DGVT2PRIB	17-May	25-Oct	6.42
C - Sg	2019	No-Till	04G234	DGVT2PRIB	6-Jun	24-Oct	6.42

C - Sg	2020	Strip-Till	05G559	DGVT2PRIB	9-May	NA	6.42
C - Sg	2021	No-Till	05G559	DGVT2PRIB	6-May	11-Oct	6.42
C - Sg	2022	No-Till	05G559	DGVT2PRIB	10-May	1-Nov	6.42
C - Sg	2023	No-Till	05G559	DGVT2PRIB	30-May	18-Oct	6.42

----- Sorghum -----

C - Sg	2015	Strip-Till	DKS29-28	Conventional	1-Jun	24-Nov	9.88
C - Sg	2016	Strip-Till	DKS29-28	Conventional	29-May	21-Nov	9.88
C - Sg	2017	Strip-Till	DKS29-28	Conventional	26-May	5-Nov	9.88
C - Sg	2018	Strip-Till	DKS29-28	Conventional	30-May	15-Nov	9.88
C - Sg	2019	No-Till	DKS28-05	Conventional	8-Jun	14-Nov	16.06
C - Sg	2020	Strip-Till	DKS28-05	Conventional	28-May	24-Oct	16.06
C - Sg	2021	No-Till	DKS28-05	Conventional	7-Jun	19-Oct	16.06
C - Sg	2022	No-Till	DKS29-28	Conventional	4-Jun	29-Sep	16.06
C - Sg	2023	No-Till	DKS29-28	Conventional	6-Jun	9-Oct	16.06

----- Soybean -----

C - Sb	2015	Strip-Till	AG2431	RR2Y	25-May	15-Oct	39.54
C - Sb	2016	Strip-Till	AG2431	RR2Y	16-May	28-Sep	39.54
C - Sb	2017	Strip-Till	AG24X7	RR2X	31-May	13-Oct	39.54
C - Sb	2018	Strip-Till	AG28X7	RR2X	17-May	20-Oct	39.54
C - Sb	2019	No-Till	AG26X8	RR2X	6-Jun	24-Oct	39.54
C - Sb	2020	Strip-Till	AG26X8	RR2X	8-May	NA	39.54
C - Sb	2021	No-Till	AG25XF1	XF	11-May	12-Oct	39.54
C - Sb	2022	No-Till	AG23XF2	XF	22-May	30-Sep	39.54
C - Sb	2022	No-Till	AG23XF3	XF	22-May	30-Sep	39.54
C - Sb	2023	No-Till	23XF42	XF	21-May	25-Sep	34.59

----- Wheat -----

C - W	2015	No-Till	WInterHawk	Conventional	23-Oct	15-Jul	345.95
C - W	2016	No-Till	WBGrainField	Conventional	3-Nov	1-Aug	345.95
C - W	2017	No-Till	WBGrainField	Conventional	28-Oct	14-Jul	345.95

C - W	2018	No-Till	Grainfield	Conventional	27-Oct	21-Jul	345.95
C - W	2019	No-Till	Grainfield	Conventional	2-Nov	18-Jul	345.95
C - W	2020	No-Till	WBGrainField	Conventional	19-Nov	NA	345.95
C - W	2021	No-Till	WBGrainField	Conventional	7-Nov	23-Jul	345.95
C - W	2022	No-Till	WBGrainField	Conventional	12-Oct	11-Jul	345.95
C - W	2023	No-Till	WB4595	Conventional	3-Nov	2-Aug	345.95
C - C - W	2015	No-Till	WInterHawk	Conventional	23-Oct	15-Jul	345.95
C - C - W	2016	No-Till	WBGrainField	Conventional	3-Nov	1-Aug	345.95
C - C - W	2017	No-Till	WBGrainField	Conventional	28-Oct	14-Jul	345.95
C - C - W	2018	No-Till	Grainfield	Conventional	27-Oct	21-Jul	345.95
C - C - W	2019	No-Till	Grainfield	Conventional	2-Nov	18-Jul	345.95
C - C - W	2020	No-Till	WBGrainField	Conventional	19-Nov	NA	345.95
C - C - W	2021	No-Till	WBGrainField	Conventional	7-Nov	23-Jul	345.95
C - C - W	2022	No-Till	WBGrainField	Conventional	12-Oct	11-Jul	345.95
C - C - W	2023	No-Till	WB4595	Conventional	3-Nov	2-Aug	345.95

Note: Rotation codes: CC = continuous corn; C-W = corn-wheat; C-Sb = corn-soybean; C-Sg = corn-sorghum; C-C-W = corn-corn-wheat. Tillage refers to the soil preparation system prior to planting: strip-till (narrow tilled strips in the seed row) or no-till (direct seeding without prior soil disturbance). Product indicates the commercial name of the hybrid or cultivar planted. Trait denotes the genetic technology package: “Conventional” = non-transgenic; suffixes such as VT2P, VT3P, or DGV3P indicate specific biotech traits for insect resistance, herbicide tolerance, and/or drought tolerance, while RIB refers to Refuge-In-a-Bag®