Improving profitability and sustainability in dual-purpose and irrigated wheat systems

by

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Abstract

Kansas is the top wheat-producing state in the United States, producing around 7.9 Mt of grain annually. Most of this wheat is hard red winter wheat (*Triticum aestivum* L.), grown in the water-limited regions of western and central Kansas. Although rainfed grain-only production systems are dominant, Kansas is home to a diversity of other wheat production systems. This thesis explores two alternative wheat cropping systems - dual-purpose wheat and irrigated wheat - through the lenses of profitability and sustainability. The first study (chapter two) addressed dual-purpose wheat and aimed to assess and optimize timing recommendations for grazing cessation. A thorough literature review revealed that the current recommendation to terminate grazing at 1.5 cm of hollow stem lacks scientific backing. Building on this, nine years of field data from Hutchinson, Kansas, were analyzed to better inform grazing termination recommendations. Each year, dual-purpose and grain-only management experiments were sown within the same field, along with a third experiment planted with the same management as the dual-purpose plots but not defoliated and instead used to monitor crop development. Results showed that the current 1.5 cm recommendation is too late to avoid grain yield penalization, and that grain yield reduction begins at approximately 0.6 cm of hollow stem. Economic analysis further revealed that increases in forage from extended grazing rarely offset monetary losses from reduced grain yield. Chapter three examined irrigated wheat production as a strategy to improve the sustainability of groundwater use in the High Plains Aquifer. Regional-scale, sustainable irrigation targets were developed based on maintaining long-term aquifer water balance (Irr Q-stable), and crop simulations using DSSAT v4.6.1.0 (CERES-Wheat and CERES-Maize) were conducted for continuous maize, continuous wheat, and maize–wheat rotations across 30 years of historical weather in nine regions. Results demonstrated that crop choice is a

powerful driver of irrigation sustainability: continuous wheat remained within sustainable irrigation limits across all regions, whereas continuous maize frequently exceeded those limits, indicating that shifts toward wheat or maize–wheat rotations can substantially reduce groundwater pumping without reducing irrigated land area. Survey data from irrigated wheat producers supported these findings, with 85% of fields remaining below sustainable pumping thresholds. Crop modeling further showed that, while most producers already apply irrigation volumes near those required to achieve yield potential, optimizing irrigation timing enabled 77% of surveyed fields to reach within 10% of their simulated yield potential. These findings highlight that improving irrigation scheduling and agronomic management, alongside strategic crop selection, offers a pathway to increase water use efficiency. Together, these chapters provide evidence-based recommendations to improve the profitability of dual-purpose wheat and the long-term sustainability of irrigated wheat production, demonstrating how management and cropping system decisions can simultaneously support producer profitability and conserve groundwater resources in often overlooked Kansas wheat production systems.

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Chapter 1 - Introduction

Wheat has been intertwined with human civilization since its domestication roughly 10,000 years ago (Awika et al., 2011). Common expressions such as “bread and butter” or “to break bread” highlight how deeply wheat is tied to the foundations of human livelihood and connection. Today, wheat remains the most extensively cultivated cereal grain worldwide (Khalid et al., 2023), supplying approximately 55% of global carbohydrate intake and 21% of total food calories (Erenstein et al., 2022). In 2025, global wheat production reached 844.36 million metric tons (United States Department of Agriculture, Farm Service Agency. (2025). underscoring its continued central role in global food systems. Within this global context, the United States ranks as the fifth largest wheat producer, contributing about 6% of total world production (United States Department of Agriculture, Farm Service Agency. (2025). Kansas leads national production, accounting for 16.5% of the U.S. planted wheat area in 2025 (United States Department of Agriculture, Farm Service Agency. (2025). As the global population continues to rise (10.3 billion expected by the mid-2080s) and demand for staple crops increases (United Nations Department of Economic and Social Affairs, Population Division, 2024), wheat’s importance to food security will only intensify. For Kansas growers, this puts increasing emphasis on improving productivity while navigating constraints on land, water, and other essential resources.

In Kansas, the 10-year average wheat yield from 2016 to 2026 was 2.95 Mg/ha, with large variation depending on geographic location within the state and growing season conditions (United States Department of Agriculture, National Agricultural Statistics Service, 2026). Kansas spans a pronounced precipitation gradient, with eastern regions receiving 1100 mm of annual rainfall and western regions receiving as little as 450 mm (Lollato et al., 2020). This gradient strongly influences crop choices. Because of its drought tolerance and relatively low water requirements, ~500 mm of available water (Zhang et al., 2024), wheat is most heavily produced in the water-limited western and central regions of the state, where limited precipitation makes dryland production of other crops such as corn and soybeans difficult. The vast majority of Kansas wheat planted each year is hard red winter wheat (95% in 2025), grown under rainfed conditions (93.3% in 2025), and produced for grain (85.4% in 2025) (United States Department of Agriculture, Farm Service Agency, 2025). Despite these being the majority production systems, Kansas is home to a diverse range of wheat production systems.

One such system is dual-purpose wheat, in which winter wheat is managed for both forage and grain. This system allows growers to capitalize on fall and winter biomass production while still harvesting grain, providing flexibility, risk management, and a strong complement to the region's substantial cattle industry (United States Department of Agriculture, National Agricultural Statistics Service, 2022). Dual-purpose systems are typically planted with different management practices than grain-only fields (higher seeding rate, earlier planting date) with the goal of promoting biomass production (Lollato et al., 2017). Current recommendations emphasize removing cattle at first hollow stem to avoid grain yield penalties, as first hollow stem marks the onset of stem elongation and the crop's increasing sensitivity to defoliation (Holman et al., 2017). The widespread adoption of dual-purpose systems in Kansas reflects the economic importance and the need for improved, regionally relevant management guidelines.

A second, less common wheat production system in Kansas is the use of irrigation. Irrigated wheat, though representing only 6.7% of the state's total wheat area, remains an important production system. This relatively small proportion still accounts for roughly 218 thousand hectares, greater than the total wheat area in all but 14 U.S. states (United States

Department of Agriculture, Farm Service Agency, 2025). In western Kansas, irrigated wheat production is shaped by declining well capacities and long-term reductions in saturated thickness of the High Plains aquifer (Buchanan et al., 2023; Scanlon et al., 2020). Many wells have already experienced declines in pumping capacity, reducing producers' ability to meet peak water demands for crops such as corn. As a result, irrigated wheat, requiring substantially less water, can serve as a stabilizing component of rotations under diminishing groundwater availability. Regional water-management entities have implemented pumping restrictions, multi-year allocations, and conservation incentives that are expected to tighten further as groundwater levels continue to fall. In this context, irrigated wheat offers potential advantages due to its peak water demand occurring in times of lower ET demand (Kansas State University Research and Extension, 2015), its compatibility with deficit-irrigation strategies (Karrou et al., 2011; Zhang et al., 2025), and its role in rotations designed to reduce irrigation water usage (Yang et al., 2025) to sustainable levels. However, to make irrigated wheat successful, research is needed to understand how to best manage wheat in irrigated conditions and its true potential to be managed within the confines of aquifer sustainability.

Given the relevance of dual-purpose and irrigated wheat systems to Kansas producers, the overarching objectives of this thesis are i) to define optimal timing of grazing termination in dual-purpose fields to avoid grain yield penalties while considering the forage benefits of the system, and ii) to assess current management practices in irrigated wheat systems to understand the role of irrigated wheat in maintaining aquifer longevity.

Chapter 2 - Rethinking timing of grazing termination in dual-purpose wheat systems: A review and field studies

Abstract

Dual-purpose crops are managed for both forage and grain production. In the United States Great Plains region, winter wheat (*Triticum aestivum* L.) is commonly grazed by cattle (*Bos Taurus* L.). Successful management requires termination of grazing early enough to avoid grain yield penalties but late enough to produce profitable forage. Current recommendations define optimal termination as 1.5 cm of hollow stem, though this threshold is poorly supported in literature. To evaluate the accuracy of this recommendation, nine years of field data from Hutchinson, Kansas, were analyzed. Wheat varieties were grown annually in dual-purpose and grain-only experiments. Dual-purpose plots were sown early at high seeding rates and fertilized to promote fall forage production, and mechanically defoliated weekly to simulate grazing; hollow stem was measured destructively in adjacent undefoliated plots to estimate the exact day each variety reached 1.5 cm hollow stem. Grain yield responses were compared with three years of experiments grazed by cattle in El Reno, Oklahoma. Grain yield was unaffected by grazing before 0.60 cm hollow stem but declined by 1.75% per day when grazing continued beyond this point. Grazing to the recommended 1.5 cm reduced yield by 12.3%. Economic analysis indicated that forage gains from extended grazing rarely offset grain losses. These results suggest that the current 1.5 cm cessation threshold is too late. Terminating grazing at ≤0.60 cm hollow stem optimizes agronomic and economic risk in dual-purpose wheat systems. For clear interpretation, a recommendation should be made to terminate grazing at Z30, the start of stem elongation.

1. Introduction

Grazing of dual-purpose winter wheat (Triticum aestivum L.) is a management practice common in many parts of the world, including Australia (Bell et al., 2014; Dove et al., 2002), Europe (Post et al., 2019), and North America (Maulana et al., 2020; West et al., 2024). Dual-purpose wheat is typically sown earlier than grain-only (ungrazed) wheat to provide a longer vegetative period for forage production in the fall. The crop is then grazed by cattle or sheep following crown root development and through the winter dormancy period. After livestock removal, the crop recovers and is subsequently harvested for grain. Dual-purpose systems benefit farmers by providing two income sources and subsequently providing flexibility and aiding risk management (Han et al., 2026; Taylor et al., 2010). Dual-purpose crops are also being increasingly explored for their potential to optimize water use efficiency in dryland systems, utilizing grazing to reduce early-season crop transpiration (Han et al., 2026; Virgona et al., 2006).

The southern Great Plains region of the United States accounts for approximately 31% of the country's wheat production (USDA-NASS, 2015-2019a). The region also supports a substantial cattle industry. Texas, Kansas, and Nebraska ranked as the top three cattle-producing states in 2022, with a combined total of $41.3 billion USD in sales (USDA-NASS, 2022b). The importance of the wheat and cattle industries in the region, in conjunction with mild winters and a long cool season, makes the US southern Great Plains well-suited for dual-purpose winter wheat production (USDA-FSA, 2025, Figure 2.1).

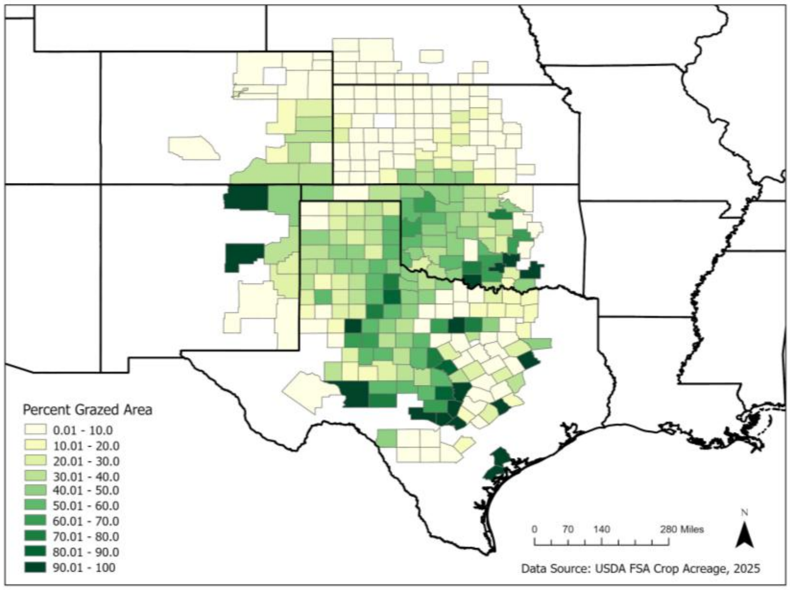

Figure 2.1. Percent of planted wheat area used for grazing by county across the southern Great Plains Region of the United States

Wheat grain yields are often lower under dual-purpose management than under grain-only management (Bell et al., 2014; Edwards et al., 2011; Han et al., 2026; Harrison et al., 2011). However, the extent of yield loss and the impact on profitability of dual-purpose crops are highly dependent on grazing intensity, sowing date, the timing of grazing termination, and potentially on cultivar selection (Butchee and Edwards, 2013; Epplin et al., 2000; Kirkegaard et al., 2012; Lollato et al., 2016; West et al., 2024). Grazing for an extended period can reduce grain yield, whereas removing cattle too early limits the potential economic benefits from the grazed forage to the cattle enterprise. It is crucial to understand the response of crop yield to delayed grazing termination so the trade-off between forage production and grain yield is optimized to maximize the overall economic benefit (Redmon et al., 1996; Taylor et al., 2010).

University Extension agencies throughout the US southern Great Plains commonly recommend removing cattle before the occurrence of the “first hollow stem” (FHS) (Edwards and Horn, 2016; Lollato et al., 2017). Hollow stem growth begins at the onset of stem elongation (Z30; Zadoks et al., 1974), after winter dormancy and immediately preceding jointing (Edwards, Carver, & Payton, 2007). In regional Extension guidance, FHS is defined as 1.5 cm of hollow stem visible underneath the developing wheat head when the main stem is split lengthwise. However, the empirical basis for this 1.5 cm threshold is poorly documented in academic literature.

The objectives of this study were to (i) identify the basis of the 1.5 cm hollow stem threshold used to define FHS, (ii) systematically determine the optimal hollow stem point to terminate grazing to avoid grain yield losses, (iii) compare system performance of grain-only and dual-purpose managements, and (iv) evaluate the economic tradeoff between grain yield losses and forage gains.

2. Materials and Methods

2.1 Literature Review

University Extension publications in the US southern Great Plains define FHS as the point at which 1.5 cm of hollow stem is visible beneath the developing wheat head and recommend that cattle be removed from dual-purpose fields at or before this stage, as measured in non-defoliated stems. However, peer-reviewed literature does not clearly establish how or why 1.5 cm became the regional definition of FHS or the recommended benchmark for grazing termination. To evaluate inconsistencies in the literature, a systematic literature review was conducted to identify how FHS had been defined in prior research and to assess whether FHS, as currently defined, is supported as the appropriate point for grazing termination to avoid grain yield losses in dual-purpose systems.

Scopus and Google Scholar were queried in May 2025 with the following search terms: ("dual-purpose" OR "dual purpose") AND "wheat" AND "First Hollow Stem". Results were filtered to include papers with 10 or more citations to focus on studies that have influenced grazing recommendations. This search terminology reflects the language used in the study region, but it is worth noting that other countries use different terminology; including this would capture a wider range of studies.

To determine the origins of regionally specific recommendations, papers were manually screened and excluded if they did not primarily focus on cattle-grazed dual-purpose winter wheat. This resulted in the exclusion of studies centered on genetics, non-grazed systems, perennial grains, sheep grazing, or alternative crops. The final database of the literature review to identify the basis for grazing recommendations based on 1.5 cm of hollow stem included 30 papers(Appendix Table A.4). Each paper was manually evaluated for its definition of FHS, citations supporting that definition (as provided through in-text citations), and metrics used to determine grazing termination in the methods sections.

2.2 Field Experiments

2.2.1 Experimental Site 1: Hutchinson, Kansas

Field experiments were conducted from 2015 to 2025 at the Kansas State University (KSU) South Central Experimental field near Hutchinson, Kansas (37.931268, -98.030163). The 2018-19 season is excluded from analysis due to data inconsistencies, freeze damage, and disease pressure. The experimental field site was characterized by Ost loam (Fine-loamy, mixed, superactive, mesic Udic Argiustolls) (Soil Survey Staff, 2026). Each year, three neighboring managements were sown within the same field. Two managements, referred to as dual-purpose and hollow stem, were designed to simulate dual-purpose management, characterized by an early sowing date and higher seeding rate. The third management was sown under grain-only management, reflecting a later sowing date and lower seeding rates typical of grain-only systems. All dates of operation are provided in Appendix Table A.1.

Each year, 16 to 36 commercially available winter wheat varieties were compared in each system. The genotypes and the number of varieties were not consistent from year to year. Within year, the same varieties were planted in each of the three neighboring managements using a randomized complete block design with four replications of each variety. Individual plot size was consistent across managements at 1.33 m by 9.14 m, consisting of 7 rows with 19.05 cm row spacing.

All experiments were sprayed with foliar fungicides at heading to avoid yield loss to disease, and each plot received 56 kg ha-1 of diammonium phosphate (18-46-00) in-furrow at sowing. A composite soil sample, consisting of 15 individual cores, was retrieved from each management trial at 0 to 15 and 15 to 60 cm depths at sowing, and nitrogen fertilizer was applied at spring green-up (~Z30) with the total amount calculated to achieve a 4.4 Mg ha-1 yield goal when accounting for the N available at sowing (Ruiz Diaz, 2024). Soil fertility levels across the nine experimental seasons are shown in Appendix Table A.2.

2.2.2 Dual-Purpose plots

Dual-purpose plots received an additional 123 kg ha-1 of nitrogen pre-plant to promote fall biomass production for grazing compared to the grain-only treatment, aiming for 6.7 Mg of dry matter per hectare fall forage production (Lollato et al., 2017). Plots were sown in mid-September at a seeding rate of 135 kg ha-1. This sowing date is earlier than optimum for wheat in this region to increase fall forage production (Munaro et al., 2020) and earlier than grain-only trials. The dual-purpose plots were mowed to a height of 1.5 cm above ground level approximately weekly throughout late winter and early spring to simulate grazing. Mowing was terminated around the time that the first varieties began measuring at 1.5 cm of hollow stem in the adjacent ungrazed hollow stem experiment proxy plots, according to local recommendations for cattle removal decisions (Redmond et al., 1996). The exact time of grazing termination (last mow) varied year to year and was recorded (Appendix Table A.1). At maturity, plant height was recorded, and plots were harvested for grain yield with a plot-scale combine, and values were moisture corrected to 13%.

2.2.3 Hollow Stem plots

The hollow stem management was managed the same as the dual-purpose experiment, except that there was no simulated grazing because local recommendations include measuring hollow stem in an ungrazed portion of the field (Redmond et al., 1996). The hollow stem trial served as a proxy for the dual-purpose trial and was used for destructive measurements to follow the crop phenology and progression of hollow stem growth. These destructive hollow stem measurements were not conducted in the dual-purpose plots to preserve accurate yield measurements. Forage was harvested from the first hollow stem plots in the fall before the anticipated start of freezing temperatures by hand clipping plants approximately 1.2 cm above the soil surface for two 1-meter by 1-row samples within each plot (Appendix Table A.1). Forage samples were placed in forced-air dryers for approximately seven days and then weighed to estimate fall biomass accumulation. Hollow stem plots were not defoliated in the spring and were instead used to destructively measure hollow stem development in each variety. Although defoliation has been shown to delay phenological development (De Oliveira Silva, 2025; Han et al., 2026; Winter & Thompson, 1987), monitoring hollow stem height in non-defoliated plots is in accordance with recommendations to check hollow stem height in ungrazed stems such as those found along fence lines. Hollow stem was measured by collecting 10 primary stems from each plot, totaling 40 stems per variety per sampling time. The primary stems were split lengthwise, and the hollow stem height visible beneath the developing wheat head was measured. Hollow stem height measurements continued weekly until the average of the stems from that variety surpassed 1.5 cm. Grain was not harvested.

2.2.4 Grain-Only plots

Grain-only trials were sown at 67 kg seed ha-1 from 2015-2019 and then increased to 84 kg seed ha-1 from 2021-2025 to better reflect the average grain-only management of winter wheat in Kansas (Jaenisch et al., 2021). Sowing occurred in mid-October, consistent with standard management for grain-only winter wheat production in the region (Jaenisch et al., 2021). Grain-only trials were harvested at maturity with a plot-scale combine, and values were corrected to 13% moisture.

2.3 Experimental Site 2: El Reno, Oklahoma

Dual-purpose and grain-only field experiments were conducted near El Reno, Oklahoma (35.532936, -97.932036) for three growing seasons from 2021-2024. The experimental field site was characterized by Dale silt loam soils (Fine-silty, mixed, superactive, thermic Pachic Haplustolls) (Soil Survey Staff, 2026). Harvest, sowing, and grazing dates are provided in Appendix Table A.3. Nitrogen was applied for a yield goal of 4.0 Mg per hectare, with 7 Kg N per hectare and 22 kg P2O5 per hectare applied at sowing in the form of ammonium polyphosphate (10-34-0).

Similar to the Kansas plots, winter wheat varieties were not consistent among years. Within each year, the same varieties were planted in each of the two managements. Within management, the designs were randomized complete block design with four replications of each variety. Harvested area for each variety was 1.52 by 5.79 m.

2.3.1 Dual-Purpose plots

Plots were sown at 135 kg ha-1 seeding rate in September, earlier than the grain-only management. Fields were grazed by cattle from late winter to early spring, aiming to remove cattle before 1.5 cm of hollow stem in line with local management. Stocking rates were 345 (2023-24), 230 (2022-23), and 348 (2021-22) kg of animal body weight per hectare, respectively. Plots were harvested at maturity and moisture corrected to 13% moisture.

2.3.2 Grain-Only plots

Plots were sown at 67 kg ha-1 seeding rate in October in accordance with standard management for the region (Munaro et al., 2020). Plots were harvested at maturity and moisture corrected to 13% moisture.

2.4 Statistical analysis

2.4.1 Yield variation across managements

Yield was analyzed using a mixed effects ANOVA in which plot type (dual purpose vs. grain only) was treated as a fixed effect, and rep nested in variety, nested within year was included as a random effect to account for the hierarchical structure of the experiment. The model can be expressed as:

EQ 1 $$y_{ijkl} = \mu + T_i + Y_j + V_{k(j)} + P_{l(k,j)} + \varepsilon_{ijkl}$$

Where, $y_{ijkl}$is yield, μ is the overall mean, $T_i$is the fixed effect of trial type, $Y_j$is the random effect of year, $V_{k(j)}$is the random effect of variety k nested within year j, $P_{l(k,j)}$ is the random effect of replicate l, nested in variety k and year j, and $\varepsilon_{ijk}$is the residual error.

2.4.2 Point of Defoliation Termination

Hollow stem measurements taken every week often did not measure an exact hollow stem height of 1.5 cm due to time gaps between measurements. To estimate the exact day that each plot reached 1.5 cm hollow stem, an exponential growth model was fitted to hollow stem measurements and day of year for each year/variety combination (Eq 2). This model was used to determine the exact day of year (DOY) when hollow stem height reached 1.5 cm. Model performance was evaluated using mean absolute error, which averaged 0.18 cm across plots (Appendix Figure A.1), indicating good predictive ability.

$$y_i = \rho_0 * ({\rho_1}^{x_i}) + \varepsilon_i$$

EQ 2 $$\varepsilon_i \sim N(0, \sigma^2)$$

Where, y_i is the response variable (hollow stem height) for the i^{th} observation, ρ_0 is the parameter that scales the output, ρ_1 is the base of the exponential, x_i is the predictor variable (DOY) for the i^{th} observation, ε_i is the residual. Residuals are normally distributed with mean zero.

To quantify grazing timing in relation to stem development, the DOY at which each variety reached 1.5 cm hollow stem in ungrazed stems was subtracted from the DOY of the final occurrence of simulated grazing. This difference represents the timing of grazing termination in days, relative to 1.5 cm, with negative values indicating termination at or before 1.5 cm and positive values indicating termination after 1.5 cm.

2.4.3 Grain Yield Penalty

Grain yield penalty was defined as the dual-purpose grain yield relative to the ungrazed grain yield, for each variety-year according to the following equation;

EQ 3 $$Yield\ penalty\ \% = \frac{Y_{dp} - Y_{go}}{Y_{go}} * 100$$

Where, Y_{dp} is dual-purpose yield, and Y_{go} is grain-only yield.

2.4.4 Linear Plateau

The relationship between yield penalty and time of grazing termination (calendar days relative to 1.5 cm) can be described with a linear plateau-type response, namely

EQ 4 $$y_i = \begin{cases} \beta_0 + \beta_1 * C + \varepsilon_i\ , when\ x \leq C \\ \beta_0 + \beta_1 * x_i + \varepsilon_i\ , when\ x > C \end{cases}$$

$$\varepsilon_i \sim N(0, \sigma^2)$$

Where C is the breakpoint of the plateau, y_i is the response variable (yield penalty %) for the i^{th} observation, β_0 is the intercept, β_1 is the slope that models the yield loss after the breakpoint, x_i is the predictor (time of grazing termination; days centered at 1.5 cm hollow stem) for the i^{th} observation, ε_i is the residual. Residuals are normally distributed with mean zero.

2.4.5 Hollow stem height at the onset of yield penalty

The breakpoint C, determined by equation 3, indicates the number of grazing days before 1.5 cm of hollow stem that the yield penalty begins accumulating. Equation 2 was utilized to determine the height of hollow stem at breakpoint C for each year-variety combination. This produced values of hollow stem heights at which grazing became detrimental to yield. Data points were then classified according to early or late grazing termination, based on whether grazing was terminated before or after this critical hollow stem height.

2.5 Economic Analysis

Economic impacts of grazing were analyzed as the relationship between forage gains and grain yield losses (as compared to the ungrazed potential). Operational costs and expenses such as supplemental feed were not considered here. Daily grain yield loss for each day grazing continued beyond C was set as β1 percent of the ungrazed yield potential (Eq 4). This daily grain yield loss was economically valued across a range of possible market prices from 0 to 0.35 $ per kg. The economic value of forage was valued by its potential to increase cattle body weight. Since cattle sale prices are highly dependent on the class and weight of cattle at the time of sale, value was illustrated across a range of value of gains (VOG) from 0 to 4.4 $ per kg. VOG is the increase in value from a one-kilogram increase in body weight. Potential forage gain from continued grazing and, therefore, body weight increases are dependent on the stocking rate and quality of forage. For this reason, economic analysis was conducted across three scenarios, accounting for 1.5, 2.75, and 4 kg per day per hectare gains (Holman et al., 2017; McCormick et al., 2021). The economic balance across a gridded surface was calculated for each pixel as such;

EQ 5 $$\text{Profit}_{\$/\text{ha/day}} = \left(\text{Grain loss}_{\text{kg/ha/day}} \times \text{Grain price}_{\$/\text{kg}}\right) - \left(\text{VOG}_{\$/\text{kg}} \times \text{BW gain}_{\text{kg/ha/day}}\right)$$

Each pixel represents the loss or profit for a single day of grazing beyond critical point C. With the assumption that this relationship is linear, the daily profit/loss can be multiplied by the number of days grazing continues beyond C for an extended time scale. This flexible structure avoids a strict assumption on stocking rate and instead bases gains on a per-unit-area basis that can be determined for a specific operation by multiplying the stocking rate by the expected gain per head. Similarly, utilizing VOG instead of market prices for a specific weight and class of animal maintains applicability across a wide range of operations.

3. Results

3.1 Literature Review

After screening titles and abstracts for relevance, 30 papers were included in the final database of our literature review, aiming to identify the basis for grazing recommendations based on 1.5 cm of hollow stem (Appendix Table A.4). Among the 30 papers reviewed, definitions of FHS varied widely. Four papers explicitly defined FHS as 1.5 cm of hollow stem, eight defined it as the point when hollow stem is first detectable above the crown, four defined FHS using wheat developmental scales (Feekes 5 or Z30; Large, 1954; Zadoks et al., 1974), and fourteen utilized the term "first hollow stem" without providing a definition.

Citation analysis revealed that nine papers cited Redmon et al. (1996) and two cited Redmon et al. (1995) as the basis for determining FHS as the target point for grazing termination (Appendix Figure A.2). Redmon et al. (1995), the earliest source identified, explicitly notes the lack of a uniform definition of first hollow stem and emphasized the need for consistent, biologically meaningful indicators for grazing termination, a concern that our literature review indicates remains unresolved three decades later.

Redmon et al. (1996) refined the point of grazing termination by defining the earliest part of the jointing growth stage as first hollow stem, specifically "First hollow stem is the growth stage at which hollow stem can first be identified above the crown in the larger wheat shoots of ungrazed wheat and occurs prior to the growing point (head) reaching the soil surface". Importantly, this definition refers to the first visible appearance of hollow stem (aligning with Z30) and does not specify a stem length threshold of 1.5 cm, which occurs closer to Z31 or Z32. Despite Redmon et al. (1996) documenting yield losses when grazing continued beyond the first visible appearance of hollow stem, current Extension recommendations in the US southern Great

Plains define FHS as 1.5 cm of hollow stem, a distinctly later developmental stage. Extension and academic sources frequently cite Redmon et al. (1996) to support this recommendation, despite the discrepancy between Redmon's definition and the benchmark being promoted. Fieser (2006) defines FHS as first visible hollow stem but also acknowledges that recommendations are to terminate grazing before 1.5 cm, leaving the first hollow stem used to terminate grazing in the research methods ambiguous. Taylor (2010) describes FHS as occurring at 0.5 inches of hollow stem but relied on synthesized data from Redmon (1996) and Fieser (2006), both of which associate yield penalties with grazing beyond first visible hollow stem rather than a fixed stem length.

Of the four papers defining FHS using growth stages, two referenced Z30, one referenced Feekes 5, and one the onset of stem elongation. All of these definitions align with the start of stem elongation, prior to the first node being visible at the stem base. This most closely aligns with the first visible hollow stem as the growing point begins to emerge above the soil surface. Nineteen of the reviewed papers originated from Oklahoma, including all four that used a 1.5 cm benchmark. The remaining studies are distributed across other US Great Plains states such as Kansas, Nebraska, Texas, and Wyoming, and other countries such as Pakistan (2), Australia, Brazil, Argentina, and China (one each).

Critically, no paper included in this review, or cited by papers within it, presented experimental evidence evaluating grazing termination relative to hollow stem height that would justify a specific 1.5 cm threshold. The only studies explicitly measuring grazing termination in relation to grain yield losses are Redmon et al. (1996) and Fieser (2006), both of which associated yield penalties with grazing beyond the first visible appearance of hollow stem (Z30).

As such, the empirical basis for terminating grazing at a length of 1.5 cm of hollow stem remains unresolved.

Collectively, the literature provides stronger support to terminate grazing at the first visible appearance of hollow stem rather than at a fixed stem length of 1.5 cm. However, as noted by Redmon et al. (1995), the lack of a consistently defined and experimentally validated grazing termination point persists. This uncertainty motivated the following analyses, which aimed to empirically evaluate grazing termination relative to hollow stem development and quantify associated agronomic and economic outcomes.

3.2 Field experiments

3.2.1 Environmental characterization of field sites and yield overview

Across the study years, the mean in-season precipitation was 499 mm with a minimum of 287 mm in the 2017-18 growing season, and a maximum of 651 mm in 2024-25 (Figure 2.2; Appendix Figure A.3). Meanwhile, cumulative seasonal alfalfa-based reference evapotranspiration (ET) ranged from 920 to 1067 mm, resulting in water demand to water supply ratios ranging from 1.6 to 3.6. Across sources of variation, average grain yield ranged from 3.4 to 4.5 Mg ha-1 in the grain-only trials and from 2.1 to 4.2 Mg ha-1 in the dual-purpose trials (Figure 2.2). Lower precipitation, and higher water demand years (2017-18, 2022-23, 2023-24) corresponded to lower yield potentials, as defined by grain-only management (Figure 2.2C).
In El Reno, OK, mean in-season precipitation was 528 mm with a minimum of 497 mm in the 2021-22 growing season and a maximum of 557 mm in 2022-23 (Appendix Figure A.4).

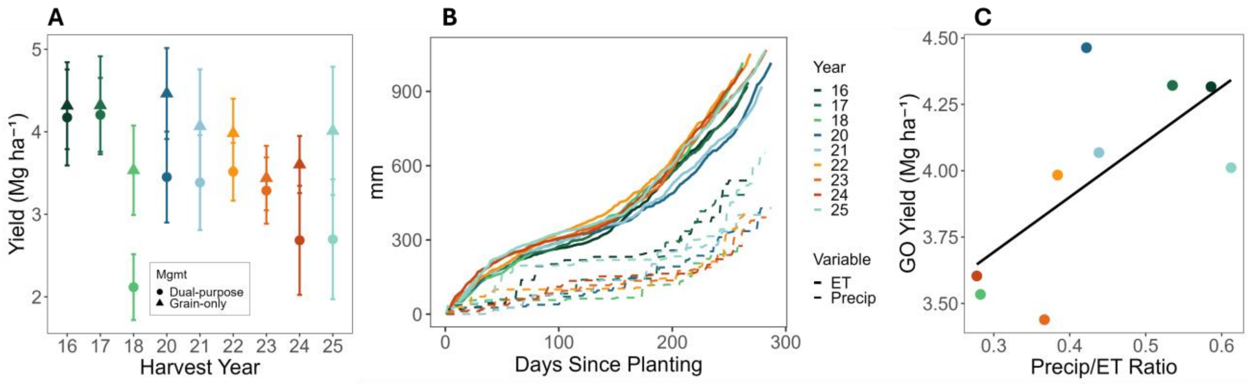

Figure 2.2. Field data from Hutchinson, Kansas. (A) Average grain yield for grain-only (triangle) and dual-purpose managements (circle). Error bars depict 1 standard deviation above and below the mean values for each management. (B) Cumulative precipitation (dashed lines) and reference evapotranspiration (solid lines), measured in alfalfa (ET) for each experimental year. Weather data was obtained from 'Hutch10SW' Kansas Mesonet station located at 37.931°, -98.02° (Kansas Mesonet, 2024). (C) Relationship between grain-only grain yields and seasonal water supply to demand ratios (precipitation/ET).

Mixed-effects ANOVA analysis showed that trial type (grain-only versus dual-purpose) had a highly significant effect on yield ($p < 0.001$). Grain-only plots yielded 3980 kg ha^{-1}, whereas dual-purpose plots yielded 3273 kg ha^{-1}, a reduction of 707 kg ha^{-1} or 18%. Random effect variance components indicated substantial yield variation among years (SD = 489 kg ha^{-1}) and among varieties within years (SD = 296 kg ha^{-1}). This ANOVA was conducted across all dual-purpose data regardless of time of grazing termination. Yearly differences in grain-only and dual-purpose yields are visible in Figure 2.2B; however, years with the largest differences between management types, such as 2018, 2024, and 2025, are also years in which grazing was terminated later into crop development.

3.2.2 Experiment 1: Grain yield penalties in relation to hollow stem development

3.2.2.1 Yield Penalty response to time of grazing termination

The relationship between yield penalty and time of final defoliation (grazing termination) relative to 1.5 cm hollow stem (measured in undefoliated proxy plots) was modeled with a linear plateau function (Figure 2.3). This model reflects the expectation that yield penalties remain stable up to a critical point, after which penalties increase as grazing termination is delayed further into the season. The breakpoint in the plateau model, representing the onset of yield penalty accumulation, occurred -5.7 days before 1.5 cm hollow stem (95% CI [-8.2, -3.2]). Prior to this breakpoint, yield penalty remained relatively constant, with a plateau value of −2.3% (95% CI [−4.8 to 0.2]). Beyond the breakpoint, yield penalty increased linearly at a rate of 1.8% d-1 of delayed grazing termination (95% CI [1.53 to 2.0]). When grazing was terminated in accordance with regional recommendation (i.e., at 1.5 cm hollow stem, x = 0), the predicted yield penalty was 12.3% (95% CI [10.1 to 14.4%]), corresponding to a yield loss of 492 ± 3 kg ha-1.

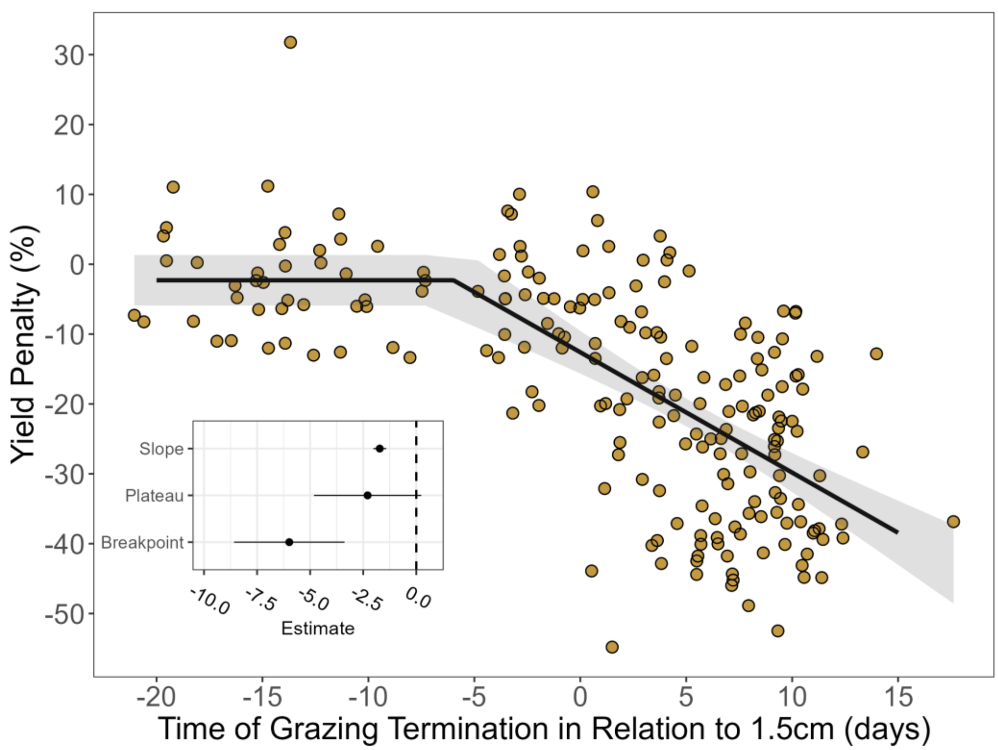

Figure 2.3. Relationship between time of grazing termination relative to 1.5 cm of hollow stem grain yield penalty under dual-purpose management. Negative yield penalty represents a reduction in grain yield under dual-purpose management compared to grain-only management. An x-value of 0 represents grazing terminated at 1.5 cm of hollow stem. The inset plot displays linear plateau parameter values and 95% confidence intervals.

3.2.2.2 Hollow stem height at the onset of yield penalty

The fitted exponential hollow stem growth models were further used to estimate hollow stem height at the breakpoint identified in the linear plateau analysis (−5.7 days relative to 1.5 cm) for each year–variety combination. Across the dataset, the mean hollow stem height at which yield penalty began to accumulate was 0.60 ± 0.03 cm (95% CI). A relatively large standard deviation of 0.20 cm indicates considerable variation in the yield penalty breakpoint due to variety and year influences (Figure 2.4). Yield penalties in dual-purpose systems began to accumulate between 0.23 and 1.05 cm of hollow stem, with the majority of combinations suffering yield loss between 0.40 and 0.80 cm of hollow stem.

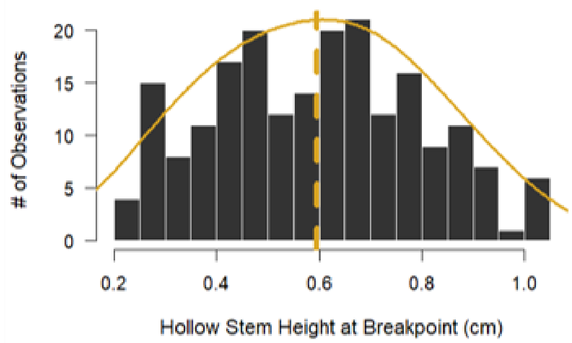

Figure 2.4. Distribution of hollow stem heights at the onset of yield penalty in each year-variety (as determined by the plateau breakpoint). Yellow dashed line denotes the average value of 0.60 cm (standard deviation of 0.20).

3.2.3 Experiment 2: Simulated defoliation compared to cattle grazing

Results from field trials in El Reno, Oklahoma, where crops were grazed by cattle and terminated before 1.5 cm hollow stem, showed an overall yield penalty of −8.1% (SE ±5.3) for dual-purpose relative to grain-only management. In contrast, trials in Hutchinson, Kansas, using simulated grazing showed a smaller yield penalty of −4.7% (SE ±0.95) when grazing was terminated at or before 1.5 cm hollow stem (Figure 2.5). Here, a breakpoint of 1.5 cm hollow stem was utilized to allow accurate comparison to the grazed experimental design, which terminated grazing using the 1.5 cm hollow stem benchmark.

Oklahoma trials showed no statistically significant differences in test weight between grazed and ungrazed treatments, while in Kansas, simulated grazing trials test weight increased by 8.01% when grazing was terminated at or before 1.5 cm hollow stem (Figure 2.5).

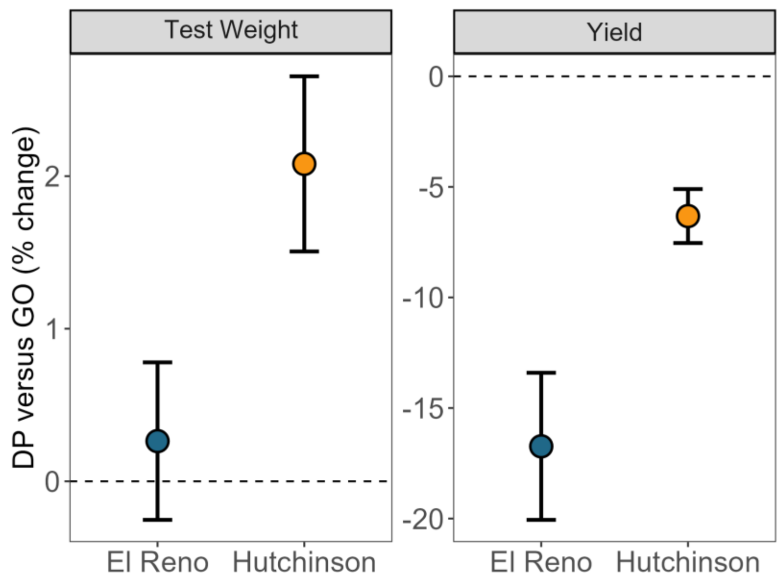

Figure 2.5. Comparison of percent change in test weight (left) and grain yield (right) between dual-purpose (DP) and grain-only (GO) management systems using both grazed and simulated grazing trials. Grazed trial data comes from Oklahoma 2021-2024. Simulated grazing data comes from Kansas 2015-2025 (excluding the 2018-19 season).

3.3 Grain-only versus dual-purpose management responses

When simulated grazing was terminated at or before 0.60 cm hollow stem, dual-purpose and grain-only management had comparable grain yields. Under these conditions, test weight increased with the simulated grazing, while plant height was unaffected. In contrast, when grazing was terminated after 0.60 cm hollow stem, grain yields declined under dual-purpose management, test weight was unaffected, and plant height was reduced relative to grain-only wheat (Table 1).

Table 2.1. Yield, test weight, and plant heights for dual-purpose and grain-only management under different grazing termination times. Early termination is grazing terminated at or before 0.60 cm of hollow stem and late is grazing terminated after 0.60 cm of hollow stem. Grain-only division in grazing termination follows the companion dual-purpose plot designation. Values are mean (standard error).

	Yield (Mg ha^{-1})			**Test Weight (kg hl^{-1})**			**Plant Height (cm)**		
Grazing Termination	*Dual-Purpose*	*Grain-Only*	*n*	*Dual-Purpose*	*Grain-Only*	*n*	*Dual-Purpose*	*Grain-Only*	*n*
Early	4.19 (0.05)	4.32 (0.06)	42	74.35 (0.30)	72.05 (0.52)	42	85.79 (0.97)	88.35 (1.09)	23
Late	3.05(0.05)	3.90(0.04)	162	74.06 (0.40)	75.74 (0.25)	134	66.17 (0.94)	72.55 (0.92)	133

Across all simulated grazing termination timings, grain-only management out-yielded dual-purpose management, averaging 4.01 Mg ha^{-1} (SE ± 24) and 3.29 Mg ha^{-1} (SE ± 30) (Figure 2.6, inset). Yield responses across management groups and across yield potential (assumed based on grain-only yield) are visualized in Figure 2.6. Dual-purpose wheat with early grazing termination yielded similarly to grain-only wheat in yield environments greater than 4 Mg ha-1 and outperformed grain-only wheat in lower-yielding environments. Conversely, late-terminated dual-purpose wheat yielded less than grain-only wheat in all environments, with differences increasing as environmental yield increased.

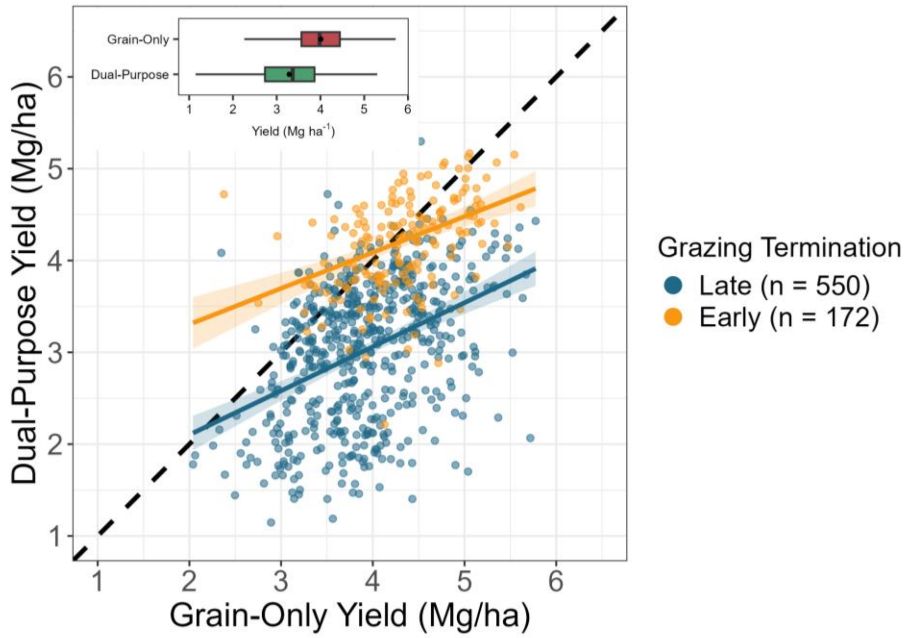

Figure 2.6. Relationship of dual-purpose and grain-only yields divided by time of grazing termination. Early (yellow) grazing was terminated at or before 0.60 cm of hollow stem, and late grazing (blue) was terminated after 0.06 cm of hollow stem. Lines are linear fit to points with parameter 95% confidence intervals. The inset plot is the overall relationship of grain-only and dual-purpose yields without consideration for time of grazing termination.

3.4 Economic tradeoffs of extended grazing

The economic viability of grazing beyond 0.60 cm hollow stem, the point at which yield penalties begin to accumulate, depends on grain and cattle market prices, forage quality, and expected daily cattle weight gain. Since a grain yield loss of 1.75% can be expected for each day of grazing beyond 0.60 cm hollow stem (Figure 2.2), based on the ungrazed yield potential; this is a grain yield loss of 70.2 kg ha-1 d-1 (SE ±0.4). Three scenarios are explored with differing levels of body weight gain per hectare expected per day (Figure 2.7). This number can be estimated as the expected body weight gain per day per head multiplied by the number of cattle per hectare. Within each scenario, the balance between grain market price per kg of grain and value of gain (VOG) per kg of body weight is compared. The values are economic outcomes for a single day of additional grazing beyond 0.60 cm hollow stem when yield penalty accumulation begins.

Forage gains rarely economically exceed grain losses from grazing past 0.60 cm hollow stem (Figure 2.7). Across all daily gain scenarios and all VOGs, when grain prices exceeded 0.25 $ per kg, net return was negative. In daily gain scenarios of 1.5 kg per day per ha, forage gains did not economically exceed grain yield losses at any point when grain market prices were above 0.1 $ per kg.

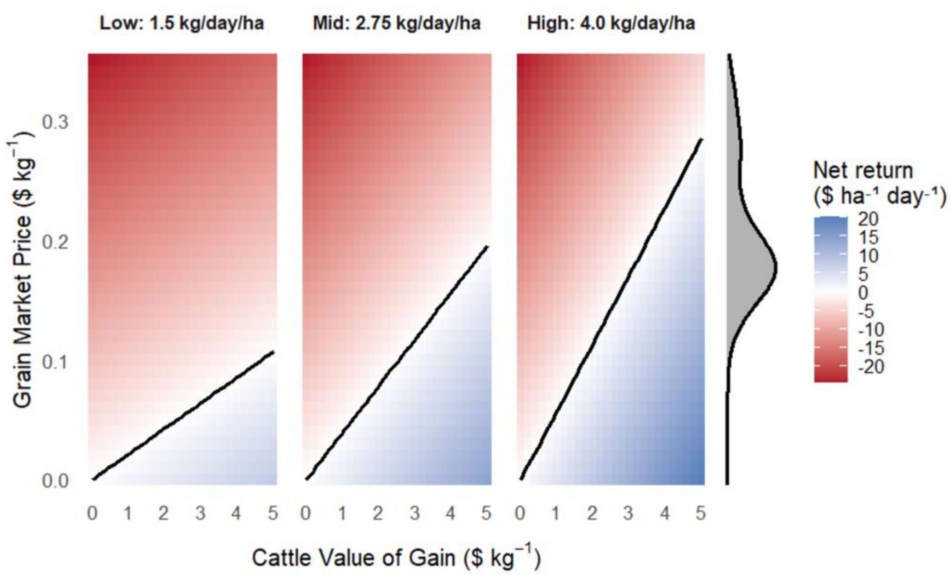

Figure 2.7. Net economic returns of grazing past 0.60 cm hollow stem. Three panels depict different levels of expected cattle body weight gain per hectare per day. Axes denote a range of grain and cattle market prices with cattle prices expressed as value of gain per pound of body weight increase. Darker red coloration is greater economic loss for each additional day of grazing compared to grazing terminated at 0.60 cm of hollow stem. The gray distribution shown on the right edge of the plots displays average US grain market prices at the time of harvest from 2016-2025.

4. Discussion

A systematic review of literature coupled with nine experimental seasons evaluating 16 to 36 winter wheat varieties per year under to two management regimes (i) identified gaps in how first hollow stem is defined, (ii) quantified yield penalty resulting from grazing, in reference to grain-only management, (iii) fine-tuned the breakpoint in hollow stem height, beyond which yield penalties from grazing are expected, (iv) estimated daily losses in yield due to grazing past such breakpoint, and (v) identified conditions under which larger yield penalties are expected.

4.1 Grain yield penalties are cumulative beyond a critical point

Grain yield penalties associated with grazing termination begin accumulating well before the widely recommended termination time threshold at 1.5 cm hollow stem. Onset of significant yield penalties occurred at 0.60 cm of hollow stem. Simulated grazing terminated before 0.60 cm of hollow stem caused no significant yield penalty, as the confidence interval for the parameter included zero (Figure 2.3). Redmon et al. (1996) reported a similar finding that no yield penalty occurred when grazing ceased prior to the first visible hollow stem. Edwards et al. (2011) also reported a 14% reduction in grain yield under grazed management when grazing is terminated at 1.5 cm of hollow stem, in line with the 12.75% yield penalization found in this study when grazing is terminated at 1.5 cm of hollow stem. Slafer et al. (2023) provided context with the assessment that yield is unresponsive to biomass removal before the critical period for grain yield, as long as biomass removal does not compromise growth during the critical period.

On the other hand, Han et al. (2026) reported a significant difference in grain yields of grazed versus ungrazed treatments, an average of 0.6 t ha-1 across three years of data, with grazing terminated prior to Z31. They concluded that although grazed crops were in a phenologically safe window, and growth rates in the critical period (Z39-Z67) were higher in grazed crops, that biomass allocation from that growth was directed to leaf and stem regrowth rather than to reproductive growth as in ungrazed plots.

Beyond the breakpoint when dual-purpose systems suffer grain yield loss relative to ungrazed wheat, the yield penalty was cumulative and increased by 1.75% a day (approximately 70.18 kg ha-1 day-1). This estimated rate of yield penalty accumulation following the critical grazing termination point was compared with values reported in the literature (Figure 2.8). Yield losses estimated from the present field trials were more conservative than those reported by Redmon et al. (1996) (80 kg ha-1 d-1), but greater than losses predicted by Fieser et al. (2006a) (1.45% d-1). For the purposes of this comparison, the plateau breakpoint identified in this study (corresponding to 0.60 cm hollow stem) was used as the effective timing of first hollow stem in our dataset.

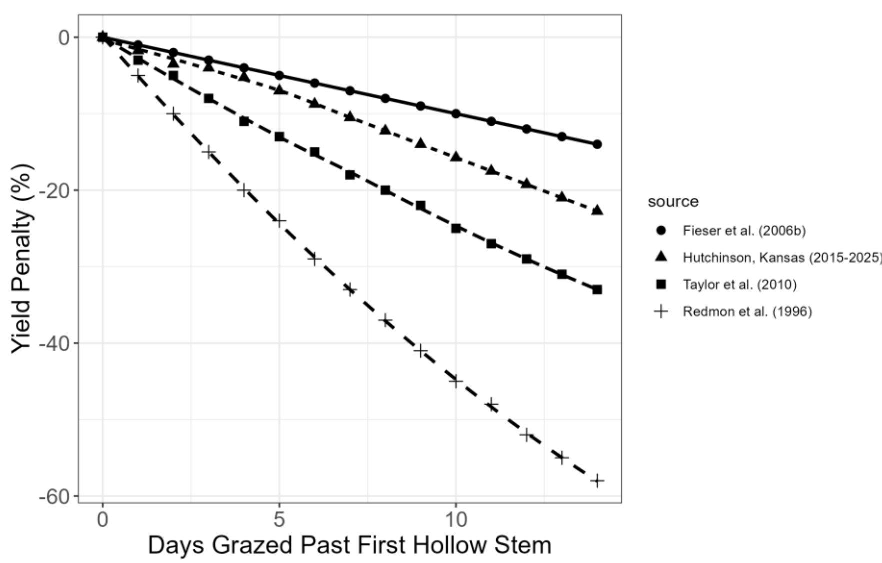

Figure 2.8. Yield penalties by grazing past the critical point in existing literature as compared to this study's field data from Hutchinson, Kansas (denoted with triangles).

Delaying termination can have two main effects on grain yield – first, there can be damage or removal of the developing spikes, causing direct yield loss as grain heads emerge above the soil surface, they become susceptible to removal and damage (Kelman & Dove., 2009; Tian et al., 2012). Secondly, the delay in termination means there is less time and potentially less residual biomass to support regrowth up to anthesis, which is the determinant of yield potential in determinate cereal crops (Bidinger et al., 1997; Kirkegaard et al., 2019; Ye et al., 2011). Consequently, even crops that are grazed in a safe phenological stage (before 0.6 cm hollow stem), if grazed heavily, may incur yield penalties if seasonal conditions are good and yield potential is high. The interaction between seasonal conditions setting the ultimate yield potential, and the timing and residual biomass remaining at termination can all generate variation in yield penalties beyond the phenological stage at termination, which explains some of the variation in yield penalties at the same termination stage shown in Figures 2.3 and 2.8.

Other factors, such as disrupting assimilate partitioning and impairing vascular development necessary for grain filling, frost damage soon after grazing, and poor leaf area development, may also contribute to grain yield reductions in grazed crops (Dunphy et al., 1982; Harrison et al., 2011; Hu et al., 2019; Pumphrey, 1970). Following defoliation, wheat development and root penetration are delayed; however, with adequate recovery time, defoliation does not reduce the resource use capacity of the crop and is not the driver of yield reduction (Han et al., 2023, 2026). In select cases, grain yield has even been shown to increase with grazing due to reduced lodging, mitigation of foliar disease, conservation of soil water, or delayed phenology leading to reduced environmental stress at anthesis (Harrison et al., 2011). All of these will interact strongly with seasonal conditions, including rainfall and the occurrence of stressful temperatures in the critical period.

4.2 Properly managed grazing increases grain test weight and maintains plant height

When defoliation was terminated prior to 0.60 cm of hollow stem, plant height was unaffected by grazing (Table 1). When grazing extended past 0.60 cm hollow stem, plant height decreased, presumably due to insufficient recovery time to maximize stem growth before anthesis (Khalil et al., 2011). Grazing increased test weight when defoliation ceased before 0.60 cm hollow stem (Table 1). The increase in test weight is most likely attributed to a reduction in heads per area so that the carbohydrates produced by the green tissue are distributed across fewer grains (Holman et al., 2017). When grazing extends beyond the critical point, the recovery ability of the plant is impacted and cannot allocate equivalent resources to carbohydrate production to drive up test weight even with reduced head number.

4.3 Grazing termination recommendations need to be conservative to avoid yield loss

Historically, FHS has been defined as the point at which hollow stem is first visible beneath the grain head. The definition of FHS as 1.5 cm hollow stem does not appear in academic literature until more recently (~2007). As such, earlier recommendations advised terminating grazing prior to hollow stem becoming visible (e.g., Arzadun, 2003; Redmon, 1996; Reuter & Horn, 2002). Simulated grazing trials in this study identify a critical point of 0.60 cm hollow stem for the onset of grain yield penalties, more closely aligning with the original conceptualization of FHS with a small biological buffer. This is consistent with the “safety zone” described by Fieser et al. (2006b) and the ‘sensitive period’ defined by Kirkegaard et al. (2019) in which yield remained stable for a short period following initial stem elongation, before declining rapidly if grazed beyond that point.

The absence of a yield penalty prior to the 0.60 cm breakpoint in simulated grazing trials suggests that this threshold represents the latest safe point for grazing with reduced changes for yield penalties. This threshold was determined from hollow-stem measurements in ungrazed plants, as grazing has been shown to delay stem elongation and developmental progression relative to ungrazed plants (De Oliveira Silva, 2025; Han et al., 2026; Winter & Thompson, 1987). As a result, the developmental status of the grazed area may be slightly behind that of the ungrazed sampled stem. Biologically, this points to the fact that grazing begins to have a detrimental impact on the crop's ability to produce its grain yield potential when stems are grazed beyond 0.60 cm of hollow stem. Sampling ungrazed plants accounts for practical limitations associated with field scouting and spatial variability and reinforces the need for conservative recommendations to avoid unintentional yield loss. While this study defines the biologically relevant threshold as 0.60 cm hollow stem, a more practical and understandable recommendation for producers is to terminate grazing at the first visible hollow stem in the ungrazed main stem, consistent with Z30, the start of stem elongation.

4.4 Alternative dual-purpose systems present similar findings

Although wheat grazed by cattle is the dominant dual-purpose crop in the US Great Plains, research has been conducted on grazing cessation in other dual-purpose cropping systems (Blümmel et al., 2020). In Australian dual-purpose canola grazed by sheep, the recommendation is to terminate grazing before bud elongation to avoid grain yield penalization (Sprague et al., 2014). Bud elongation in canola marks the transition from vegetation to the reproductive growth stages. Similarly, research on sheep-grazed wheat from Australia recommends grazing cessation at Z30, also marking the transition of the crop from vegetative to reproductive stages (Kirkegaard et al., 2015). Analysis by Seymour et al. (2015) demonstrated the sensitivity of grazing into reproductive stages in wheat, barley, and canola. These results support the adoption of a Z30 grazing termination recommendation in the US Great Plains.

4.5 Simulated grazing acts as a proxy for actual cattle grazing

Comparisons between simulated grazing trials in Kansas and cattle-grazed trials in Oklahoma revealed greater yield penalties in grazed systems, even when grazing was terminated before 1.5 cm hollow stem (Figure 5). Even larger grazing penalties from the dual-purpose system under actual grazing (c.a. 14%) were reported by Edwards et al. (2011). The larger losses likely reflect additional sources of yield loss in grazed systems that are not captured by simulated defoliation, including trampling, uprooting, uneven grazing pressure, and variability in monitoring grazing termination timing. Differences may also be attributed to variations in regrowth under continual grazing versus intermittent mowing events. Notably, in the Oklahoma dataset, one of the three site-years (2022–2023) showed increased grain yield under dual-purpose management compared to ungrazed controls. This response was attributed to earlier planting of dual-purpose wheat, which allowed crop establishment during October rainfall events prior to the onset of extreme drought conditions that coincided with grain-only planting and persisted through the remainder of the season.

Furthermore, the exact hollow stem height at grazing termination in these cattle-grazed trials is uncertain and only defined as occurring before 1.5 cm of hollow stem. Cattle-grazed trials exhibited larger grain penalty variation, which could be due to the varied stocking rates across the three years of data. Cattle are known to be selective grazers that will graze more heavily in areas of more palatable wheat varieties (West et al., 2024; Zhang & Huang, 2025). Non-reported preferential feeding in this experiment may also contribute to the larger variability compared to simulated defoliation, as varieties differed year to year. However, the use of simulated defoliation ensures that results remain controlled and are not confounded by the variability of preferential grazing introduced by animals.

These findings suggest that simulated grazing may underestimate baseline yield penalties, in some environments, associated with actual cattle grazing, regardless of grazing timing. Consequently, recommendations based solely on simulated grazing trials may not be sufficiently conservative for cattle-grazed systems. If some degree of yield penalty is unavoidable under cattle grazing, then adopting an earlier grazing termination threshold, such as first visible hollow stem, becomes even more critical to mitigating economic risk.

While removal of developing grain heads is a well-recognized cause of yield loss when grazing extends into stem elongation, several additional mechanisms likely contribute to the observed penalties (Kelman & Dove, 2009; Tian et al., 2012). Grazing during reproductive development can reduce tiller survival, disrupt assimilate partitioning, and impair vascular development necessary for grain filling (Dunphy et al., 1982; Hu et al., 2019; Pumphrey, 1970). Physical damage from grazing and trampling may further reduce canopy photosynthetic capacity and stand uniformity, exacerbating yield losses beyond what would be expected from mechanical defoliation. Cattle-grazed trials showed no change in test weight between grazed and ungrazed plots, which differs from previous studies in the same region (Edwards et al., 2011). We note in passing that this may be a function of the small dataset, since the comparison of neighboring trials using only three years of data may provide insufficient statistical power when considering trial as the fixed effect and year as a random effect.

4.6 Extended grazing of forages does not compensate for the economic loss of grain yield

Although grain yields may be comparable between dual-purpose and grain-only systems when grazing is terminated early, this economic comparison does not account for the substantially higher seeding rates typically used in dual-purpose wheat, often double those of grain-only systems, and the increased nitrogen inputs. Increased input costs influence the relative profitability of dual-purpose management as compared to grain-only management.

Within dual-purpose management, decisions such as cultivar selection (West et al., 2024) and grazing termination timing remain critical in determining profitability. Results from this study demonstrate that grazing even a single day beyond 0.60 cm hollow stem consistently reduced grain yield and net economic returns, even when accounting for increased weight gains (Figure 7). These findings are consistent with previous economic analyses showing that extended grazing is rarely profitable except under scenarios of low grain prices, strong cattle markets, and high daily weight gains (Redmon et al., 1996; Taylor et al, 2010). Further research is needed to understand these dynamics under varied yield potentials, because in low-yielding environments, late grazing has a less detrimental impact on grain yield.

In years of low grain yield potential, producers commonly elect to graze out (forgo grain harvest) their crops. The economic analysis performed here assumes grain yield is being reduced from the yield potential. In reality, in years of lower grain yield potential, the loss due to an additional day of grazing would be proportionally less.

These tradeoffs demonstrate that dual-purpose systems also offer economic benefits of risk management and system flexibility with grazing income offsetting grain production risks in dry seasons and adding value in wet seasons (Han et al., 2026; Simao et al., 2024). Additionally, grazing reduces transpiration through green biomass in the fall season, where water is often limited, and due to reductions in deep soil root biomass, grazing also reduces water uptake from deep soil layers later in the growing season (Han et al., 2024), which can potentially help to explain the greater yields seldom measured in dual-purpose as opposed to grain-only trials.

Earlier sown dual-purpose crops also spread labor demands and may benefit whole farm operations by enabling earlier sown across the board.

Additionally, the observed increase in test weight under early grazing aligns with previous studies suggesting that reduced head density and improved assimilate availability per grain may enhance grain quality in grazed systems, thus improving profit when there are premiums offered for greater test weight (Holman et al, 2017).

4.7 Management context and limitations

These field trials did not explicitly account for grazing intensity, which is a critical determinant of yield outcomes in dual-purpose wheat systems (Butchee & Edwards., 2011; Ochsner et al., 2017). The effect of grazing intensity is a product of residual biomass remaining and the subsequent ability of the crop to recover (Kirkegaard et al., 2019). This is of relevance in the simulated versus actual grazing comparisons when grazing intensity is not specifically defined to allow a one-to-one comparison.

Likewise, sowing date remains a key factor influencing the success of dual-purpose systems. Earlier sowing is needed to maximize forage yield, and often reduces wheat grain yield (Edwards et al., 2011); although it can at times result in greater yields, as demonstrated by the 2022–2023 Oklahoma site-year (in this case, by allowing the dual-purpose wheat to capitalize on fall precipitation before severe drought conditions). In years when heat and drought stress occur close to maturation, delayed phenology resulting from grazing may be detrimental to grain yield (Harrison et al., 2011), highlighting the environmental effects at play in determining the success of dual-purpose crops. Earlier sowing also lengthens the period of vegetative growth prior to vernalizing temperatures, increasing fall forage production; it may have a separate effect on grain yield if there is drought escape.

Finally, simulated grazing trials were not conducted with grazing termination times evenly spaced across developmental time; instead, mowing termination occurred for all varieties on the same calendar date. While this study was favored by creating a range of first hollow stems at which mowing was terminated, including more observations with earlier-terminated grazing (<1.5 cm hollow stem) would improve the specificity of future termination recommendations. Future work integrating grazing intensity, environmental conditions, and the timing of grazing termination, as well as the interactions among these factors, is necessary to improve dual-purpose decision-making.

5. Conclusions

A review of 30 influential studies on dual-purpose wheat revealed substantial inconsistencies in how FHS has been defined in relation to hollow stem height and grazing termination. The academic literature does not provide a clear scientific basis for the development of the 1.5 cm hollow stem threshold as the recommended point for grazing termination. Instead, a larger body of literature supports defining FHS, and corresponding grazing termination recommendations, as the point when hollow stem first becomes visible.

Analysis of nine years of simulated grazing trials conducted in Hutchinson, Kansas, identified the onset of grain yield penalty at approximately 0.60 cm hollow stem. Prior to this threshold, dual-purpose and grain-only systems had the potential to yield comparably. Beyond this breakpoint, grain yield declined at a rate of approximately 1.8 % d-1 with continued grazing. Results from cattle-grazed trials in El Reno, Oklahoma, suggest that yield penalties may be greater under actual cattle-grazing as compared to mowing. However, additional research is needed to fully assess the extent to which simulated grazing accurately represents cattle grazing systems.

In most scenarios, grazing beyond 0.60 cm hollow stem resulted in net economic losses. Additional daily forage gains from extended grazing rarely outweighed daily grain yield losses. On a day-by-day basis, grazing beyond 0.60 cm hollow stem was only profitable under conditions of exceptionally low grain prices, high cattle prices, and high forage quality. Given the consistent economic and severe agronomic disadvantages of grazing beyond this threshold, recommendations to terminate grazing in regional Extension publications should be made conservatively. Terminating grazing at 1.5 cm hollow stem results in avoidable grain yield penalties. These findings indicate that the current recommendation to terminate grazing at 1.5 cm hollow stem is not sufficiently conservative to prevent grain yield loss. To better reflect both academic literature and field-based evidence, grazing should be terminated at or before the first visible signs of hollow stem, as measured on the main stem of an ungrazed wheat plant, aligning with Z30, the very start of stem elongation. Terminating grazing at or before 0.60 cm hollow stem has the potential to eliminate grain yield losses, increase test weights, and maximize forage benefits of dual-purpose wheat.

Acknowledgements

Oklahoma Mesonet data are provided courtesy of the Oklahoma Mesonet, which is jointly operated by Oklahoma State University and the University of Oklahoma. Continued funding for maintenance of the network is provided by the taxpayers of Oklahoma."
We acknowledge the ongoing support of the Kansas Wheat Commission in ensuring field research such as this experiment conducted in Hutchinson, KS, can operate.

Chapter 3 - Irrigated wheat for groundwater sustainability in the High Plains Aquifer region: Integrating long-term simulations with farmer management data

Abstract

Declining groundwater availability in the High Plains Aquifer threatens the long-term sustainability of irrigated agriculture in the U.S. Great Plains, where crop selection and irrigation management decisions strongly influence water demand. This study calculated a scalable irrigation sustainability metric (Irr Q-stable) to define region-level irrigation thresholds based on aquifer water balances and evaluated the role of crop choice and management in reducing groundwater depletion. Required reductions in current irrigation use ranged from 4 to 38% depending on region, with the greatest reductions needed in western Kansas. We hypothesize that more frequent wheat under irrigation, as compared to the current predominant continuous maize systems, will reduce water withdrawal needs in the region to sustainable levels. Thirty years of crop modeling simulations were used to compare irrigation requirements and water sustainability outcomes among continuous maize, continuous wheat, and maize–wheat rotations in ten regions across western and central Kansas. Simulations were conducted under fully irrigated, non-limited conditions, with irrigation applied to maintain plant-available soil water levels between 50 and 90%. Simulations demonstrated that fully irrigated wheat consistently remained below Irr Q-stable thresholds across all regions, whereas continuous maize frequently exceeded sustainable irrigation limits, indicating that crop choice is a critical strategy for reducing groundwater demand. Some continuous maize systems required irrigation reductions

exceeding 50%, suggesting that sustainability goals are likely not achievable through irrigation efficiency improvements in maize alone. In contrast, wheat required reductions of no more than 8% across all regions and five-year periods, levels that may be achievable through improved management and irrigation technology. Additionally, a survey of irrigated wheat fields was conducted to characterize current management practices, irrigation inputs, and opportunities to improve water use efficiency (WUE). Survey-based simulations indicated that 42% of irrigated wheat fields could increase yields through improved irrigation timing without increasing total irrigation volume. Sustainability metrics, long-term crop simulations, and producer management data demonstrated the potential of irrigated wheat to maintain productivity while reducing groundwater depletion, and to identify management opportunities to further improve wheat WUE.

1. Introduction

The Great Plains region of the United States (U.S.) contains more than 30% of the nation's agricultural land and accounts for more than half of the total national wheat (*Triticum aestivum L.*) production (Parton et al., 2014). Kansas, which consistently ranks as the top wheat-producing state, generates an estimated $1.44 billion annually from wheat production alone (Kansas Department of Agriculture, 2025). Despite this economic and agronomic importance, wheat yields in the central U.S. have remained largely stagnant since the early 1990s (Patrignani et al., 2014; Grassini et al., 2013), and statewide wheat acreage has steadily declined during the same period (Simao et al., 2024; USDA-NASS, 2025). Much of this decline reflects a shift toward maize (*Zea mays L.*) production, which supports the region's cattle industry and has benefited from rapid technological advancements in hybrids, fertility management, and production systems (Holman et al., 2024).

The expansion of maize production in western Kansas is tightly coupled with increasing demand for irrigation. Previous research in this region has suggested that maize requires a minimum of 900 mm of total water supply (plant-available water at sowing, precipitation, and irrigation) to approach an estimated yield potential of about 19.4 Mg ha^{-1}, considering that about 100 mm of that are lost via evaporation (Grassini et al., 2011; Moghbel et al., 2024). Meanwhile wheat, traditionally produced under dryland conditions, may require 450 mm or less to reach a yield potential of ~ 5.2 Mg ha^{-1} considering evaporative water losses of ~ 80 mm in this region (Patrignani et al., 2014; Lollato et al., 2017). Kansas exhibits a strong east–west precipitation gradient, with much of western Kansas receiving approximately 450 mm of annual precipitation. Consequently, achieving high yields of water-intensive crops relies heavily on irrigation, increasing pressure on limited groundwater resources.

Irrigation capacity in western Kansas depends almost entirely on the High Plains Aquifer, which has experienced severe depletion in recent decades. Some areas have lost more than 60% of their saturated thickness, and projections suggest that approximately 35% of the U.S. southern Great Plains is in danger of losing irrigation capacity within the next 30 to 50 years (Haacker et al., 2015; Rhodes et al., 2023; Scanlon et al., 2012). As irrigation availability declines, producers will increasingly need to consider cropping systems that maintain profitability while reducing groundwater demand to ensure the stabilization of aquifer water levels, extending the lifetime of regional groundwater resources. The key questions become: How much does irrigation pumping need to be reduced to achieve stable aquifer levels, and what management strategies, including crop selection and rotation, can realistically achieve these reductions?

Crop selection represents one of the most direct opportunities to reduce agricultural water demand (Deines et al., 2019; Drastig et al., 2016). Although irrigated wheat represents approximately 7% of Kansas's irrigated cropland, this acreage exceeds the total wheat area produced in many U.S. states under both dryland and irrigated systems combined (USDA FSA, 2025). Because wheat requires less seasonal water supply than maize, increasing the role of wheat within irrigated cropping systems may provide an opportunity to reduce groundwater withdrawals while maintaining agricultural production. However, the sustainability benefits of wheat depend not only on crop choice but also on optimizing management practices that improve yield and water use efficiency (WUE, hereafter defined as yield produced per unit of water available). Improvements in irrigation timing, nutrient management, and other agronomic practices can increase crop productivity per unit of water, allowing producers to maintain yields while reducing unnecessary irrigation inputs (Liu et al., 2022; Hochman et al., 2009; Sadras & Lawson, 2013; Alharbi et al., 2004).

We hypothesize that greater frequency of wheat under irrigation has the potential to produce high-yielding crops while improving the sustainability of the High Plains aquifer, as opposed to the current system that is predominantly continuous irrigated maize. Additionally, we hypothesize that current irrigated wheat management in Kansas can be improved to increase WUE and yield with simple changes to agronomic and irrigation management.

To evaluate these hypotheses, this study integrates two complementary approaches: First, we used long-term crop modeling simulations evaluating how alternative crop sequences influence irrigation requirements and maintenance of water levels in the US High Plains Aquifer. This exercise was followed by a farmer survey documenting current management practices in irrigated wheat fields across Kansas. Together, these approaches aim to (i) determine sustainable irrigation limits needed to extend the usable life of the High Plains Aquifer, (ii) quantify the influence of crop sequence on irrigation requirements under sustainable groundwater use targets, and (iii) characterize current management practices in Kansas irrigated wheat systems to identify opportunities for improving production and WUE.

2. Methods

2.1 Study region

Kansas is the largest wheat-producing state in the United States, producing approximately 7.9 Mt of grain across 3.0 Mha annually (10-year average; USDA NASS, 2025; USDA NASS, 2026). Winter wheat is typically sown from mid-September through mid-November and harvested from early June through early July, with timing varying by environment, year, and crop sequence (Munaro et al., 2020). In 2025, Kansas also produced 23 Mt of maize on 2.7 Mha (USDA NASS, 2026). Maize planting typically occurs from mid-April through late May, and harvest occurs from September through October (Long et al., 2017).

This study focused on central and western Kansas, where the majority of irrigated land in Kansas is located. Annual precipitation ranges from approximately 450 mm in western Kansas to 750 mm in central Kansas (Lollato et al., 2020; Kansas Mesonet, 2026). Climatic conditions also vary substantially across the region, with winter temperatures ranging from approximately -3°C in northern Kansas to summer temperature maximums exceeding 27°C in south-central Kansas (Kansas Mesonet, 2026). These differences in climate and water availability contribute to variation in crop water demand and irrigation sustainability among regions in the state.

To ensure appropriate geographic coverage in our analysis, we used the climate zones delineated by the Global Yield Gap Atlas (YPYGA, 2026; www.yieldgap.com), which follows a standardized approach for defining spatially representative agricultural regions. Briefly, the protocol first defines climate zones within the study area based on three parameters influencing yield potential: (i) aridity index, which indicates the degree of water limitation, (ii) annual total growing degree day (T_{base}: 0ºC), indicating the length of the growing season, and (iii) temperature seasonality, which serves to quantify the degree of temperature oscillation during the year (Van Wart et al., 2013; Bussel et al., 2015). Within each climate zone, reference weather stations were selected to provide daily weather data for crop simulations. A 100 km radius buffer region was created around each weather station and masked to the climate zone boundaries, so that only areas falling within the same climate zone and weather station were considered. When more than one station was available within a climate zone, stations were prioritized based on the amount of target wheat area covered by their masked buffer regions and the length and completeness of their daily weather data (Romero Soler et al., 2026).

These regions were further filtered to include only regions containing sufficient groundwater and water-use observations for estimating irrigation sustainability thresholds. Specifically, regions were retained if they contained at least five observations for both annual water-level change and water use for each year from 2000 through 2025. Regions were named according to the central municipalities they encompass. The resulting ten regions represent distinct agro-climatic and groundwater-use regions, encompassing 91% of all Kansas irrigated winter wheat (2025 planted area), 83% of Kansas irrigated maize (2025 planted area) (U.S.

Department of Agriculture, Farm Service Agency [USDA FSA], 2025), and 97% of the total aquifer extent in Kansas (Figure 3.1a,b)

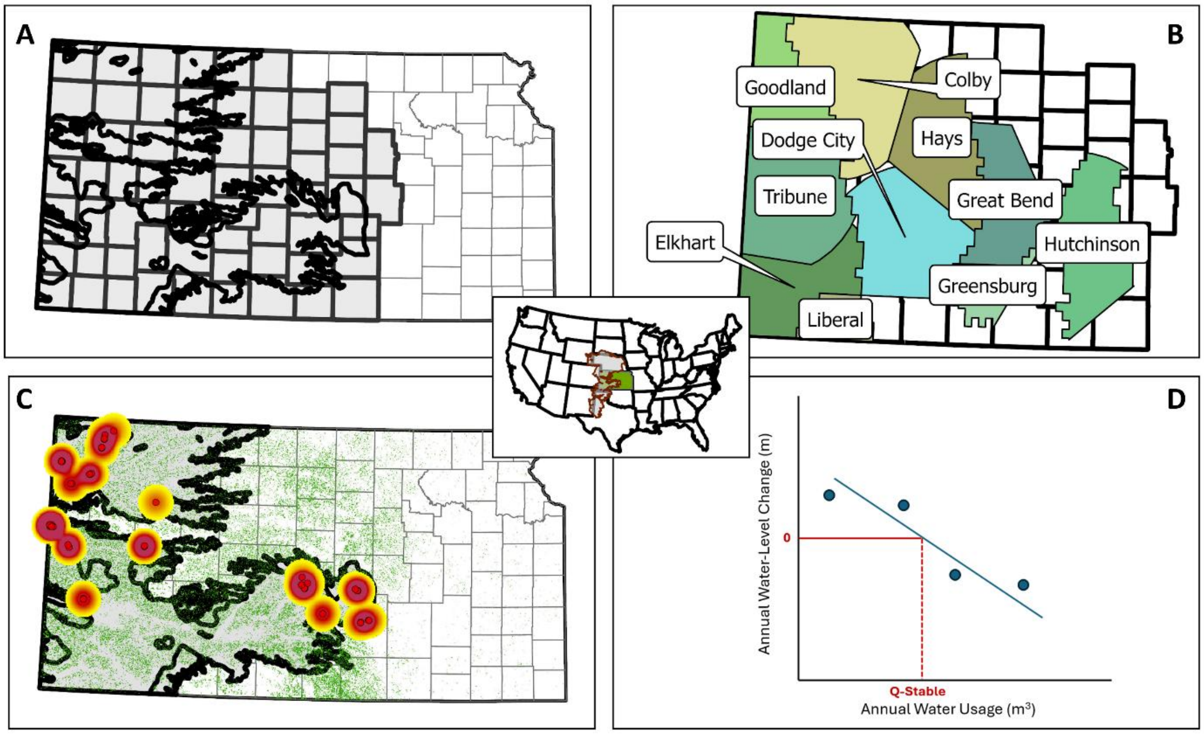

Figure 3.1 Visual depiction of methods. (A) Map of Kansas maize (yellow raster) and wheat (green raster) planted areas in 2024. Solid line shows the extent of the High Plains Aquifer in Kansas, and gray shaded counties depict the study area shown in panel B. (B) Map of the ten regions defined for central and western Kansas overlaid on Kansas counties. (C) Surveyed irrigated wheat field locations within the State of Kansas. The outline of the High Plains aquifer is overlaid across Kansas. Red points are specific field locations. To avoid overlapping points and fields that are reported across multiple years, a heat map surrounds the field points with darker red colors indicating higher density of reported fields and yellow being more sparse locations. (D) Graphical depiction of the linear relationship used to compute Q-stable sustainable pumping limits. The dashed red line is the value of Q-stable, where the y-axis is equal to zero. Blue points represent different years of data, with the blue linear regression line fit to the points. The central panel denotes the location of Kansas (green) and the High Plains aquifer (red) within the United States.

2.2 Sustainable irrigation targets

In this study, sustainable irrigation was defined as levels of water withdrawn leading to the stabilization of aquifer water levels.

2.2.1 Dataset

The relationship between groundwater withdrawals and aquifer response impact the estimates of sustainable irrigation limits. Since 1978, every nondomestic pumping well in Kansas has been required to have a water right that specifies the maximum annual water use for that well, and a water use report for each water right must be submitted annually (Butler et al., 2016). Since 1990, that data is then released, after quality-control checks, by the Division of Water Resources of the Kansas Department of Agriculture by the fall of that year (Wilson et al., 2005). Our analysis considered the reported values for wells from 2000 to 2025. Pumping records from the Division of Water Resources of the Kansas Department of Agriculture not only report the volume of water usage for each water right, but they also categorize the usage of that water as domestic, industrial, municipal, recreation, stockwater, or irrigation. The report also includes the land area serviced by each water right.

Water-level measurements of the High Plains Aquifer from the Kansas Geological Survey from 2000 to 2025 were also utilized in this work (Bohling & Wilson, 2012; Kansas Geological Survey., n.d). Annual water-level change was calculated as the difference between consecutive annual measurements of depth to groundwater at each monitoring well. Negative values represented declining groundwater levels, whereas positive values represented groundwater recovery. Measurements were aggregated within each region to estimate the regional annual aquifer response. Water-level and water-usage measurements were filtered to sites within the defined geographic regions (Appendix Figure B.1).

2.2.2 Computation of Q-stable

Q-stable represents the annual pumping volume associated with zero groundwater-level change. To estimate the level of pumping that leads to approximately stable aquifer water levels at a time scale of several years to decades, the following methodology was used as defined by Butler et al. (2016), for each of the ten regions.

Q-stable was estimated by fitting a linear relationship between annual groundwater-level change and annual groundwater withdrawals within each region (Figure 3.1d):

$$\Delta WL = \beta_0 + \beta_1 Q \qquad \textbf{Eq 1.}$$

where ΔWL represents annual groundwater-level change, and Q represents annual groundwater withdrawal. The pumping level at which predicted groundwater-level change equals zero was calculated as:

$$Qstable = -\frac{\beta 1}{\beta 0} \qquad \textbf{Eq 2.}$$

Uncertainty in the Q-stable estimate was determined using a 95% confidence interval on the defined linear relationship and subsequently carried into the uncertainty of when water-level change is equal to zero.

2.3.3 Irrigation targets

Because Q-stable represents total groundwater withdrawal from all sectors, it does not directly represent irrigation sustainability. Therefore, Q-stable was partitioned to estimate the portion of sustainable pumping available specifically for irrigation (Equation 3).

The average non-irrigation water for each region was calculated from 2020 through 2024. The 5-year average was treated as a representation of current non-irrigation water usage, smoothing yearly fluctuations using a 5-year trend. The sum of non-irrigation water per region was subtracted from the Q-stable values. The resulting value was the sustainable volume of water available to each region for irrigation. The sustainable irrigation volume was then divided by the total area of irrigated land (averaged from 2020 through 2024) in each region to bring the target volume to the field scale. Irrigated land area was determined as the sum of land area reported by water rights in each region.

This resulting value, termed Irr Q-stable, represents the maximum annual irrigation volume per hectare that is compatible with long-term groundwater-level stabilization.

$$Irrigation\ Q_{stable} = \frac{(Q_{stable} - non\ irrigation\ pumping)}{irrigated\ land\ area} \qquad \textbf{Eq 3.}$$

2.3. Crop modeling

2.3.1 Crop model calibration and validation

Cropping systems were modeled using CERES-wheat and CERES-maize, embedded in DSSAT v 4.8.5.0 (Jones et al., 2003). CERES models are process-based models that simulate crop growth and development as a function of weather, soil conditions, genotype, and crop management (Jones & Kiniry 1986; Ritchie & Otter, 1985). Soil water balance accounts for precipitation, evapotranspiration, infiltration, drainage, and surface runoff, while crop development is driven by temperature and genotype-specific coefficients. Biomass accumulation is estimated from intercepted photosynthetically active radiation and radiation use efficiency, and grain yield is determined from plant density, grain number, and grain weight at maturity, affected by temperature, water availability, and assimilate availability (Jones & Kiniry 1986; Ritchie & Otter, 1985).

Crop genetic coefficients were calibrated for this analysis based on data from well-managed experiments conducted with locally adapted varieties across the study region. For wheat, genetic coefficients for the cultivar 'IBA' were calibrated using 12-site years of field data from central Oklahoma harvest in 2013 and 2014 (Lollato & Edwards, 2015). Model performance was validated against 38 independent site-years using the highest-yielding cultivar at each site-year to determine whether the parametrization adequately reproduced the phenology and yield potential of locally adapted wheat varieties. Root mean squared error (RMSE) for yield was 1.01 Mg ha^{-1} for calibration and 1.10 Mg ha^{-1} for validation (Appendix Figure B.2). Information on each site year used for validation is available in Appendix Table B.1. For maize, 9 site-years of field observations from 4 locations in Kansas, using locally adapted varieties, were compared with simulations generated using 35 DSSAT CERES-Maize cultivar parameter set (Allen, 1996). Complete information on the 9 site-years of maize data is available in Appendix Table B.2. Each parameter set was evaluated based on its ability to simulate the field data for phenology and yield. The parametrization for 'Pioneer 3489' provided the best overall agreement with the field observations and was therefore selected for the maize simulations (RMSE 2.34 Mg ha^{-1} for yield and 18 days for maturity; Appendix Figure B.2).

2.3.2 Weather and soils for crop modeling

Within each region, one to three dominant soil mapping units (taxonomic orders) were identified based on Soil Survey Geographic Database (SSURGO; Survey Soil Staff, 2026) to capture the soil conditions representing the majority of agricultural production within each region. Soil texture and depth were retrieved directly, while other variables needed for crop simulations, such as plant-available water-holding capacity, bulk density, and other soil water hydrological parameters, were estimated from the reported soil properties and generic relationships reported in the literature and using pedotransfer equations when not available directly from SSURGO (Saxton and Rawls, 2006). For survey data simulations, soil type was determined using field-specific coordinates.

For long-term simulations, wheat harvested area within each soil type and within each region, was calculated. The number of soil types modeled for each region was then based on including as many profiles as were needed to cover >50% of the wheat area within the region (i.e. the dominant soil types for wheat area with each region were selected) (YPYGA, 2026; IFPRI, 2019). Soil types simulated for each region are reported in Appendix Table B.3. Soil profile depths ranged from 1.4 to 1.9 m and included mollisols, entisols, vertisols, and alfisols. Measured daily weather data (minimum and maximum air temperature, solar radiation, and precipitation) were retrieved from Daymet, daily Surface Weather Data On a 1-km Grid selected because its gridded daily weather products provide spatially continuous climate data suitable for field-scale crop simulation across heterogeneous agricultural landscapes (Mourtzinis et al., 2017). For survey simulations, weather was gathered using field-specific coordinates. For long-term simulations, coordinates were based on the coordinates of the reference weather station within each region (Appendix Table B.5; Appendix Figure B.5). Simulations were conducted under no-till management with residue retained post-harvest and full establishment regardless of residue status at planting.

2.4. Long-term simulations

2.4.1 Management and timescale

Long-term simulations were conducted for three fully irrigated crop sequences: continuous maize (CC), maize-wheat (CW), and continuous wheat (WW). The simulations included 35 primary crop harvest years, from 1991 through 2025. The first five years of the simulations (1991-1995) were considered a ‘warm-up’ period to achieve accurate initial soil water and residue conditions. The 30 years of data from 1996 to 2025 are treated as the study period for all analyses.

For the maize-wheat sequence, simulations were run in two offsetting year cycles to capture each crop harvest in all years (i.e., avoid the effect of alternating year sequences). The fallow period between crops was explicitly specified to have no irrigation or nutrients applied to ensure that soil water and residue conditions carried over between crops. For all simulations (long-term and survey data), water balance was active, but nutrients were non-limiting. Automatic irrigation was triggered when plant-available soil water within a fixed management depth declined to 50% of capacity and was applied until plant-available soil water reached 90% of capacity (Araya et al., 2021; Onyekwelu et al., 2025). This management depth was set at 100 cm for maize and 50 cm for wheat (Araya et al., 2021) and represents a static soil profile depth used solely to evaluate the irrigation trigger; it is distinct from simulated rooting depth, which the model determines dynamically as a function of crop growth stage. All irrigation applications were simulated using sprinkler irrigation with an application efficiency of 90%. No maximum was set per single irrigation event. The objective of these simulations was not to predict individual field behavior, but rather to compare relative differences in irrigation requirements among cropping systems under consistent management assumptions.

Planting dates for each crop were selected based on optimal regional averages for each region, informed by extension bulletins, variety performance trials, and local agronomists (Appendix Table B.5; Shroyer et al., 1996). Simulated wheat planting dates were also verified against the surveyed wheat fields and found to be representative.

2.4.2 Data Analysis

2.4.2.1 Irrigation water use in 5-year windows

Most Kansas water right holders are eligible to apply for a multi-year flex account (MYFA), which allows annual pumping to exceed the authorized quantity in individual years while limiting total pumping over five years to five times the annual allocation (KDA, 2025). To align simulated irrigation demand with this management framework and reduce the influence of individual anomalously wet or dry years, irrigation water use for the three simulated crop rotations was evaluated using rolling five-year windows. This approach provides a management-relevant timeframe for comparing crop-specific irrigation requirements with existing groundwater management policies and accounting for variability in annual weather conditions.

To align with the calendar year structure of water rights, total irrigation applied from January 1 through December 31 was summed for 26 consecutive five-year periods (1996–2000 through 2021–2025) for each region, soil profile, and crop rotation combination. For the maize–wheat (CW) rotation, two offset sequences were evaluated, resulting in 52 five-year windows per region and soil profile combination, to ensure that both maize and wheat phases of the rotation were represented across all years.

2.4.2.2 Sustainability of crop sequences

Irrigation applied for each crop sequence, in each region, was averaged across 5-year periods. These average values, along with 95% confidence intervals, were compared to five times the annual Irr Q-stable targets to determine average performance of crop sequences. Values above the target were considered unsustainable; values below the target were deemed sustainable as they will not lead to the depletion of aquifer saturated thickness (Whittemore et al., 2023). This approach was used to determine the percentage of 5-year periods that each region and sequence operated sustainably.

2.4.2.3 Simulated yields

Simulated crop yields were determined at maturity for maize and wheat grown continuously or in rotation. Crop yields (1996-2025) were averaged to represent the yield potential within each geographic region zone. Annual yields were also regressed against seasonal precipitation to identify yearly trends and validate that simulated water productivity fell within previously defined crop boundary functions developed in the region, including that for maize (water use efficiency of 27.7 kg ha-1 mm-1, minimum water loss of 100 mm; Grassini et al., 2011) and wheat (water use efficiency of 17.2 kg ha-1 mm-1, minimum water loss of 82 mm; Lollato et al., 2017).

2.5. Farmer Survey

2.5.1 Data collection

Field-specific coordinates, agronomic management, and grain yields were collected from 53 irrigated wheat fields harvested in 2023, 2024, and 2025 in central and western Kansas (Figure 3.1c). Wheat fields classified as irrigated were included regardless of whether irrigation was applied during the specific growing season, as the objective was to characterize management within irrigated production systems rather than only irrigated growing seasons. Participants were recruited with the help of local research and extension agencies, and all participation was voluntary. The survey captured field-level information such as sowing and harvest dates, irrigation amounts, pesticide use, seeding rate, nutrient plan, tillage, field size, and row spacing (Appendix Table B.6). Producers could report multiple fields/years of information. All data were self-reported rather than directly measured.

The survey protocol was approved by the Kansas State University Committee for Research Involving Human Subjects (protocol IRB-12545). Before each survey, producers signed a data-sharing agreement permitting the use of their responses and ensuring that only aggregated results would be reported to protect privacy.

2.5.2 Data pre-processing

All survey responses were standardized to consistent units, and categorical variables were grouped when necessary (e.g., tillage classified as no-till, minimal-till, or full-till based on grower descriptions). Variables with minimal variation in (>94% same response) were not included in statistical analysis. To account for geospatial influences on wheat yields and water use, each surveyed field was also assigned to a region based on clustering (central or west).

2.5.3 Simulation scenarios

Survey simulations were designed to separate the effects of irrigation amount from irrigation timing. Specifically, scenarios evaluated whether yield improvements could be achieved through improved irrigation scheduling without increasing seasonal irrigation volume. Simulations were completed for each surveyed field using its reported planting date under three irrigation regimes. The first scenario applied irrigation according to the specific dates and volumes reported by the producer for each specific field and year. The second scenario maintained a maximum seasonal irrigation total equal to, or below, that of the amount reported by the farmers, but allowed the irrigation timing to synchronize with the crop water demand. Here, irrigation application was set to trigger when the profile reached 50% plant-available soil water and irrigated until 90% of the plant-available soil water capacity was reached or the limit for water quantity was reached, within the top 50 cm (Araya et al., 2021; Onyekwelu et al., 2025). The final scenario was an unlimited irrigation scenario to reflect yield potential conditions. All simulations utilized the reported sowing dates but were otherwise assumed to have no nutrient limitations or yield reductions from pest or weed pressure. Simulations accounted for the effect of water limitation where applicable. Across scenarios, a minimum irrigation amount per irrigation event was set to 12.7 mm to reflect farmer practice. One surveyed field was excluded from crop modeling analyses because it had a forage crop preceding the wheat crop, for which we did not have sufficient information or model parametrization to simulate that previous crop and its effects on soil water and residue carryover.

Based on simulated crop phenology for the reported and yield potential simulations, irrigation applied at each growth stage was summed and expressed as a proportion of total seasonal irrigation. Reported and yield potential simulations were then compared to identify differences in irrigation timing, on a growth stage scale.

2.5.4 Sustainability of surveyed fields

Each field surveyed was assigned to a region (Figure 3.1) based on its geographic location. Observed irrigation volumes were compared to the annual Irr Q-stable targets for the respective regions. Additionally, the volume of water required to produce the simulated yield potential was also compared to Irr Q-stable to quantify current sustainability and sustainability of the fields under fully irrigated scenarios.

2.5.5 Factors influencing WUE

Water-use efficiency (WUE) was calculated for each surveyed field as the ratio of grain yield to total water supply (Equation 4), where the total water supply was calculated at the sum of plant available water at sowing (as defined by the crop model in each field), in-season precipitation, and applied irrigation.

$$WUE = \frac{Grain\ Yield}{Total\ Water\ Supply} \qquad \textbf{Eq. 4}$$

Water-use efficiency was modeled as a function of management practices, soil properties, and water inputs using a hierarchical Bayesian regression model (Equation 5). A hierarchical Bayesian framework was selected because survey data contained repeated observations from producers across multiple years and regions, resulting in non-independent observations and potential producer-level management effects. The model was designed to incorporate a diverse set of agronomic predictors and account for heterogeneity at the producer level, region, and year levels. All priors were set as weakly informative without strong influence over any one factor.

We assessed model convergence using R̂, effective sample size, divergent transitions, treedepth saturation, and HMC energy diagnostics. The following model defines the structure:

$$y_{ij} = \beta_0 + \sum_{k=1}^{18} \beta_k x_{k,ij} + p_j + \mathrm{d_m} + r_l + \epsilon_{ij},$$

$$\epsilon \sim N(0, \sigma^2),$$

$$p_j \sim N(0, \tau^2),$$

$$\mathrm{d_m} \sim N(0, \rho^2),$$

$$r_l \sim N(0, \varphi^2)$$

Eq. 5

Where, y_{ij} is the response variable WUE for i^{th} field within the j^{th} producer, β_0 is an overall mean, each subsequent β is a predictor k (management or environmental) of the i^{th} field within the j^{th} producer, p_j is the random effect of the j^{th} producer, normally distributed with mean zero and variance τ^2, $\mathrm{d_m}$ is the random effect of the m^{th} harvest year, normally distributed with mean zero and variance ρ^2, r_l is the random effect of the l^{th} region, normally distributed with mean zero and variance φ^2, and ε_{ij} is the error for the i^{th} field within the j^{th} producer, normally distributed with mean zero and variance σ^2.

3. Results

3.1 Sustainable irrigation targets

Relationships between groundwater withdrawals and aquifer response varied among geographic regions across central and western Kansas (Figure 3.2). Accounting for average non-irrigation water use (2020–2024) and irrigated land area, sustainable annual irrigation limits ranged from 2252.8 $m^3\ ha^{-1}$ in northwest Kansas to 3230.0 $m^3\ ha^{-1}$ in central Kansas (Table 3.1).

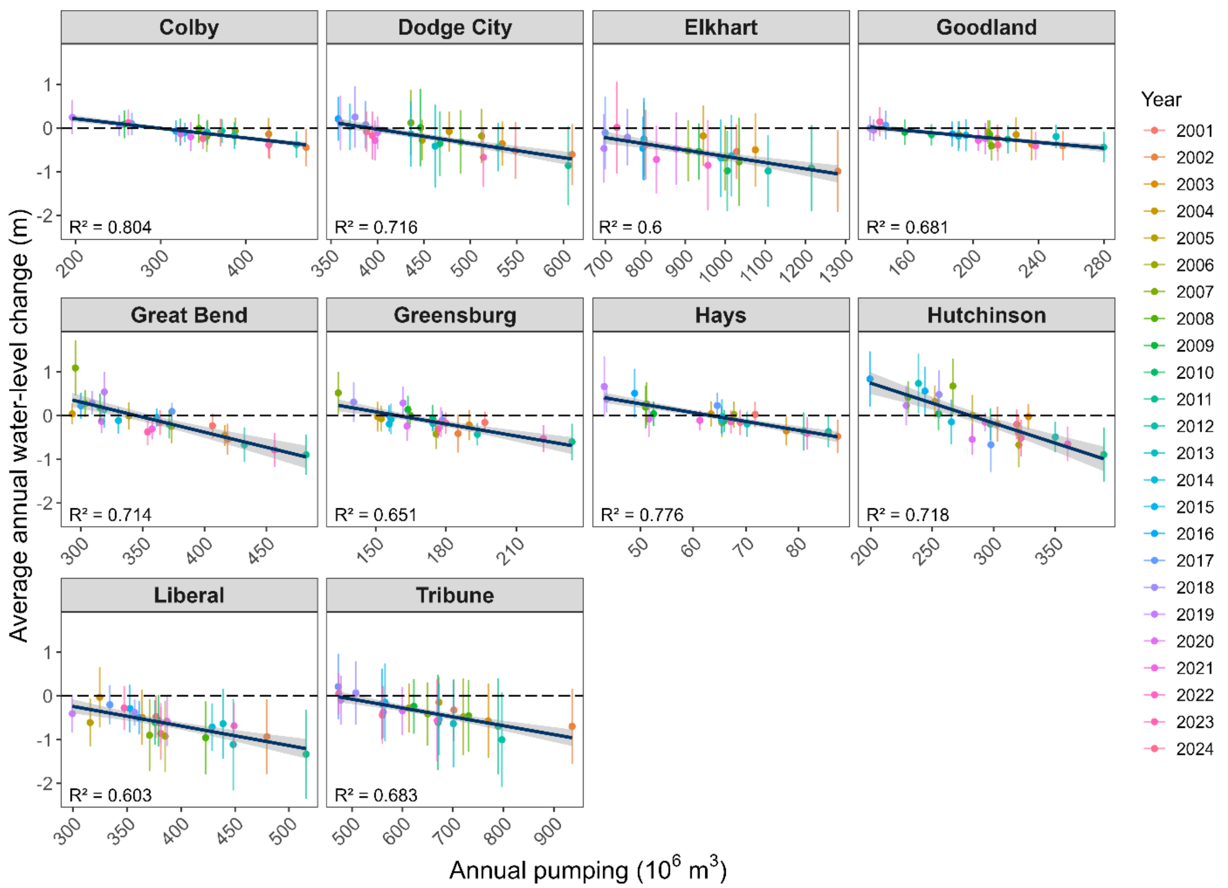

Figure 3.2 Linear relationship between water-level change and annual pumping records used to calculate Q-stable for each geographic region. Each colored point represents the averages of a given year, 2001 through 2025.

Current irrigation use exceeded sustainable irrigation limits in all regions, but the magnitude of reduction required for irrigation water usage to reach Irr Q-stable varied substantially across the state (Table 3.1). The largest reductions were required in western Kansas, where Elkhart and Liberal regions required approximately 36.2% and 37.9% reductions respectively in current irrigation use to reach Irr Q-stable. In contrast, eastern and central regions required smaller adjustments, with the Hays region requiring the lowest reduction (4.5%), followed by Great Bend (6.7%) and Dodge City regions (7.0%). These results indicate that regional differences in groundwater sustainability are driven not only by irrigation intensity check but also by differences in aquifer response and available groundwater resources.

Table 3.1 Average non-irrigation pumping, irrigation pumping, and irrigated area in each region 2020 through 2024, and the sustainable irrigation pumping limit per hectare (Irr Q-stable) for each of ten geographic regions. Percent reduction is the reduction to current irrigation use needed to reach Irr Q-stable.

Region	Non-irrigation water use (10^6 m^3)	Average irrigation use (10^6 m^3)	Average irrigated area (ha)	% Reduction needed	Irr Q-stable (m^3 ha^{-1})
Colby	11.5	329.9	116,815	13.1	**2452.0** (2302.6, 2601.3)
Dodge City	30.5	391.5	121,371	7.0	**2994.4** (2782.4, 3206.4)
Elkhart	16.9	490.2	138,252	36.2	**2257.0** (1643.8, 2870.3)
Goodland	2.8	198.3	62,119	29.5	**2252.8** (1931.6, 2574.1)
Great Bend	11.2	364.3	106,163	6.7	**3189.5** (3053.3, 3325.7)
Greensburg	5.3	175.5	46,961	13.6	**3230.0** (3058.1, 3402.0)
Hays	6.8	58.4	22,558	4.5	**2482.5** (2348.3, 2593.3)
Hutchinson	101.6	213.8	74,157	15.9	**2422.4** (2260.9, 2583.8)
Liberal	14.4	373.8	939,094	37.9	**2471.4** (1932.4, 3010.4)
Tribune	39.4	532.3	153,659	20.4	**2756.1** (2358.1, 3154.1)

3.2 Long-term simulations

Simulated maize yields averaged 15.3 Mg ha^{-1} across all regions and were highest in western Kansas locations, including Goodland, Tribune, and Colby (>17 Mg ha^{-1}). Wheat yield potential averaged 6.5 Mg ha⁻¹, with the highest yields occurring in Elkhart and Liberal (7.2 and 7.3 Mg ha⁻¹, respectively) (Appendix Figure B.3). Simulated yields fell within biologically feasible water productivities for both wheat and corn boundary functions defined by Lollato et al., 2017 and Grassini et al., 2011 (Figure 3.3).

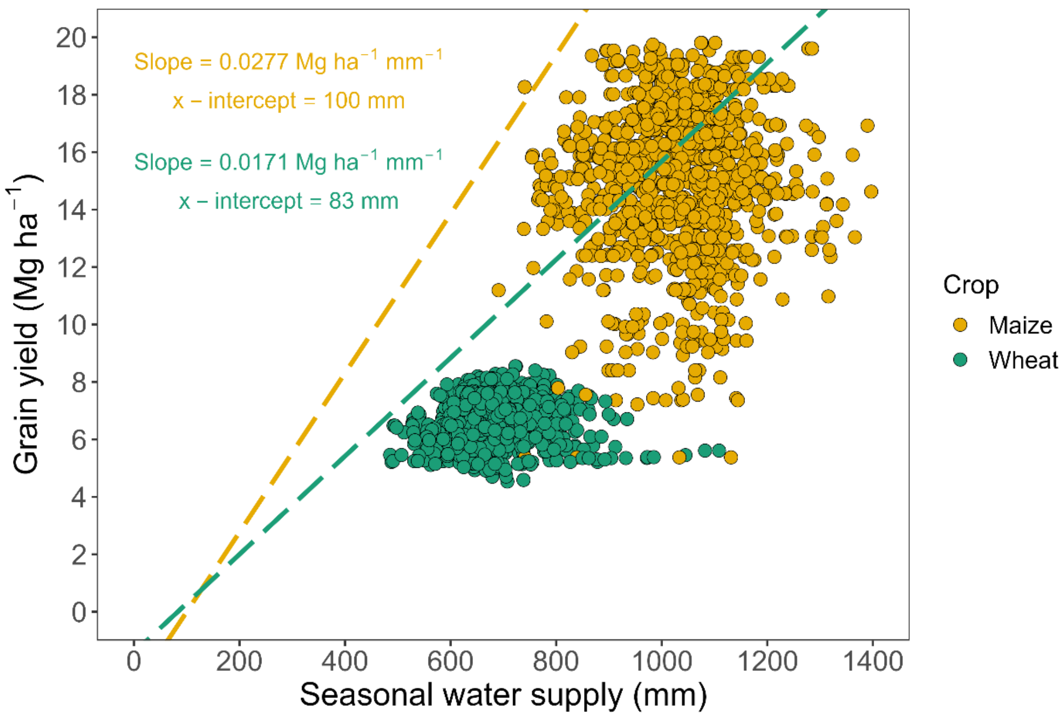

Figure 3.3 Simulated yield potentials for wheat (green) and maize (yellow) regressed on seasonal water supply (available water at sowing, plus in-season rainfall, plus applied irrigation). Yields include simulations across 30 continuous years (1996-2025) and ten regions. Dashed lines are the boundary water productivity functions for wheat and maize defined by Lollato et al., 2017 and Grassini et al., 2011 respectively.

Average irrigation requirements differed substantially between crops but were relatively consistent between rotations containing the same crop. Continuous maize and maize in maize–wheat rotations required approximately 417 mm of irrigation annually (0-809 mm), whereas wheat required approximately 275 mm annually in both continuous wheat and maize–wheat rotations (0-646 mm) (Figure 3.4A). Including plant-available water at sowing and growing-season precipitation, total water supply averaged approximately 1030 mm for maize and 688 mm for wheat. Irrigation demand varied among regions and was generally greater in drier western regions (0-775 mm) as compared to the central region (0- 400 mm), where lower precipitation required greater supplemental irrigation to maintain non-limiting water conditions (Figure 3.6b). On an annual basis, crops exceeding Irr Q-stable were associated with lower precipitation during the growing season, indicating that climate variability strongly influenced irrigation requirements (Figure 3.4b).

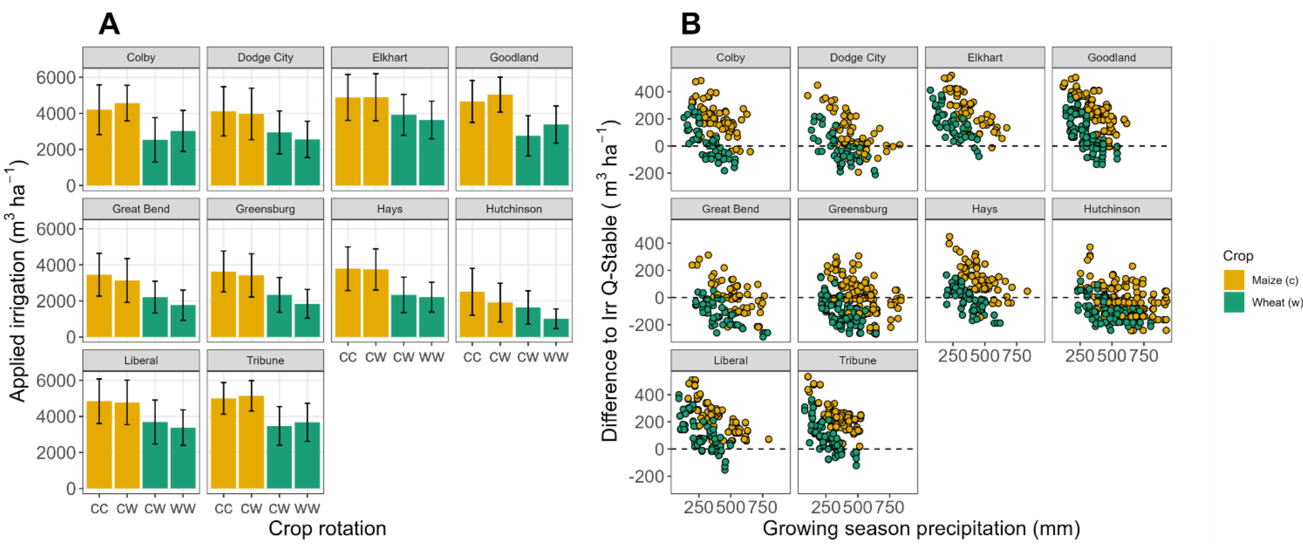

Figure 3.4 (A) Average seasonal applied irrigation for continuous maize (CC), continuous wheat (WW), and maize-wheat (CW) rotations for each crop. (B) Applied irrigation minus Irr Q-Stable for maize and wheat crops plotted against growing season precipitation. Panels depict ten geographic regions with data for simulations from 1991 to 2025.

Regarding the sustainability of irrigated rotations, continuous maize consistently required the greatest irrigation inputs and exceeded sustainable irrigation thresholds by an average of 7690 m^3 ha^{-1} across regions per five years (Figure 3.5). In seven of ten regions (i.e., Colby, Dodge City, Elkhart, Goodland, Hays, Liberal, Tribune), continuous maize irrigation exceeded Irr Q-stable in every five-year period evaluated. In the remaining regions, continuous maize remained sustainable only intermittently, ranging from 12% of periods in Greensburg to 50% in Hutchinson.

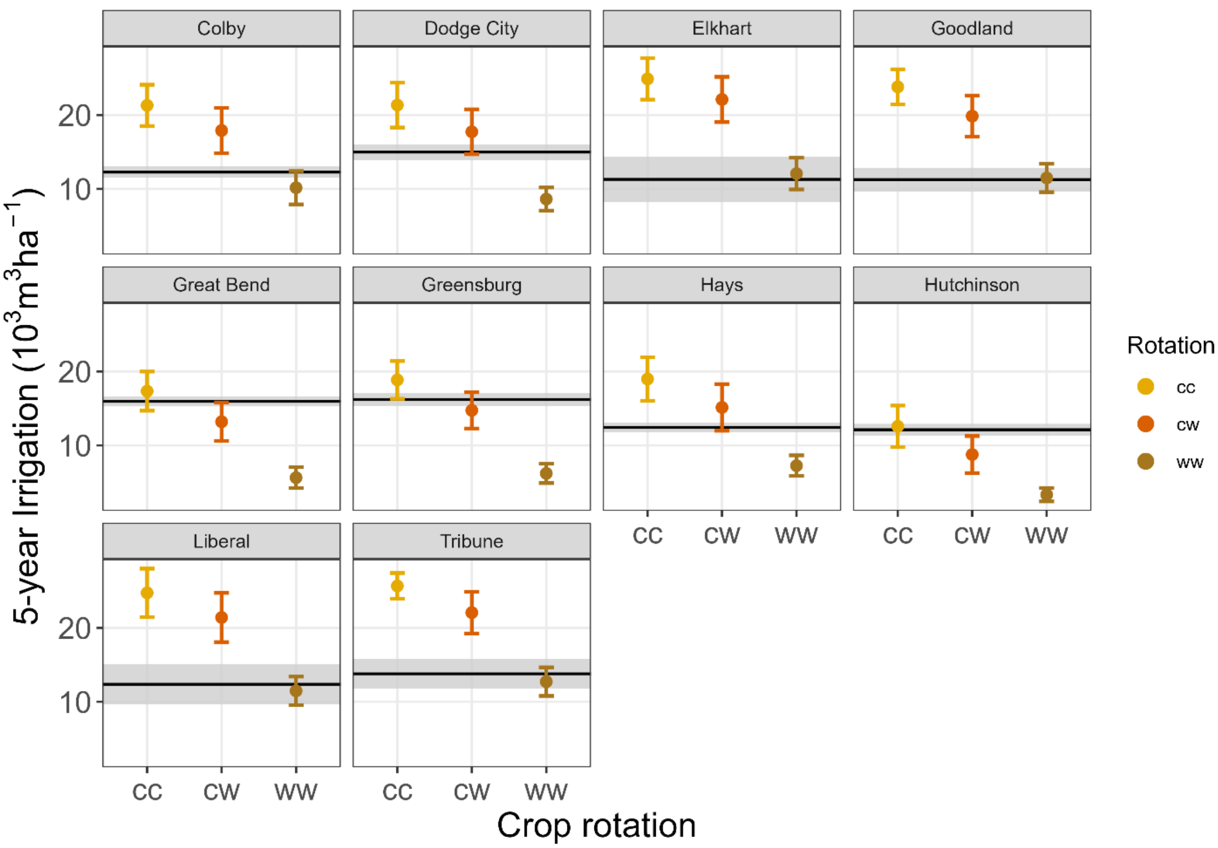

Figure 3.5 Simulated irrigation water use in 5-year time intervals compared to sustainable Irr Q-stable targets (black line, with 95% confidence interval shaded). Each panel (region) compares irrigation demand for three fully irrigated crop rotations: continuous maize (CC), continuous wheat (WW), and maize-wheat (CW) (mean and standard deviation).

In contrast, continuous wheat demonstrated substantially greater compatibility with sustainable groundwater use, using an average of 4368 m^3 ha^{-1} less than the sustainable target (Figure 3.5). Five regions remained below Irr Q-stable during all five-year periods (i.e., Dodge City, Great Bend, Greensburg, Hays, Hutchinson), while the remaining regions exceeded sustainable limits only during the driest periods. Even in Liberal and Elkhart, the regions with the largest sustainability gaps for wheat, irrigation reductions of approximately 8% were sufficient to achieve sustainability across all five-year periods. Maize–wheat rotations provided an intermediate strategy, reducing irrigation demand relative to continuous maize while maintaining maize production within the rotation (Figure 3.5). However, sustainability depended strongly on location. In the westernmost regions (i.e., Elkhart, Goodland, Liberal, and Tribune), maize–wheat rotations exceeded Irr Q-stable during all five-year periods, whereas central and eastern regions were sustainable during 4–89% of evaluated periods depending on location (Figure 3.5).

Differences among soil profiles within locations were generally small compared with differences among crop rotations and geographic regions, with minimal differences observed in irrigation demand between different soils in the same location. The largest difference occurred in Hutchinson, in which maize 5-year irrigation demand decreased around 2700 mm in Mollisols compared to Entisols (Appendix Figure B.4). Difference in irrigation demand for this same location and soil was not substantial for CW and WW rotations.

3.3 Irrigated wheat management in Kansas

3.3.1 Description of surveyed fields and management

A total of 53 irrigated wheat fields from 12 producers were surveyed across central and western Kansas during the 2023–2025 harvest seasons (Figure 3.1c). Fields represented a range of environments, management practices, and irrigation strategies within the major irrigated wheat production region of Kansas. Mean reported grain yield was 5.8 Mg ha^{-1}, ranging from 2.3 to 8.7 Mg ha^{-1}, while simulated non-limited yield potential averaged 7.4 Mg ha^{-1} (SD = 0.62).

Surveyed categorical and numeric variables were examined to understand current practices. Distributions of categorical variables are shown in Figure 3.6. A total of 92% of fields applied fungicide, 96% of fields did not apply insecticide, and 94% (50 out of 53) of fields utilized 19.05 cm row spacing. No-till was the predominant tillage system reported (60%), and most seeds were treated with both fungicide and insecticide (70%). About 55% of the fields reported a previous crop of irrigated maize, with the next most frequent previous crops being dry beans (*Phaseolus vulgaris* L.) (18%) and soybeans (*Glycine max L. (Merr.)*) (17%).

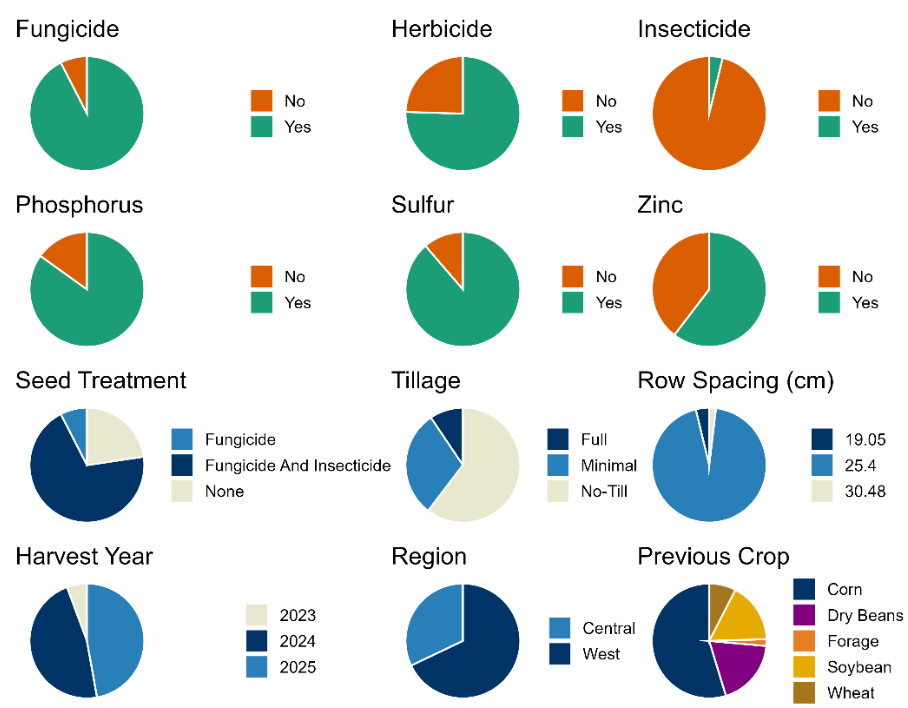

Figure 3.6 Visual distributions for categorical variables of 53 surveyed irrigated wheat fields in Kansas.

Growing season precipitation varied among survey years, ranging from 200 to 638 mm (mean = 372 mm, SD=114) and being characterized as below-average in 2023 to near-normal conditions in 2024 and variable in 2025 (USDA NASS, 2025). Across surveyed fields, applied irrigation ranged from 0 to 383 mm (mean = 162 mm, SD = 61), and plant-available water at sowing ranged from 17 to 291 mm (mean = 166 mm, SD = 61). The average nitrogen (N) applied per field was 105 kg N ha^{-1} (SD = 47), with the majority of N applications occurring in the spring around green-up. Soil texture across surveyed fields was predominantly silt-dominant (Figure 3.7)

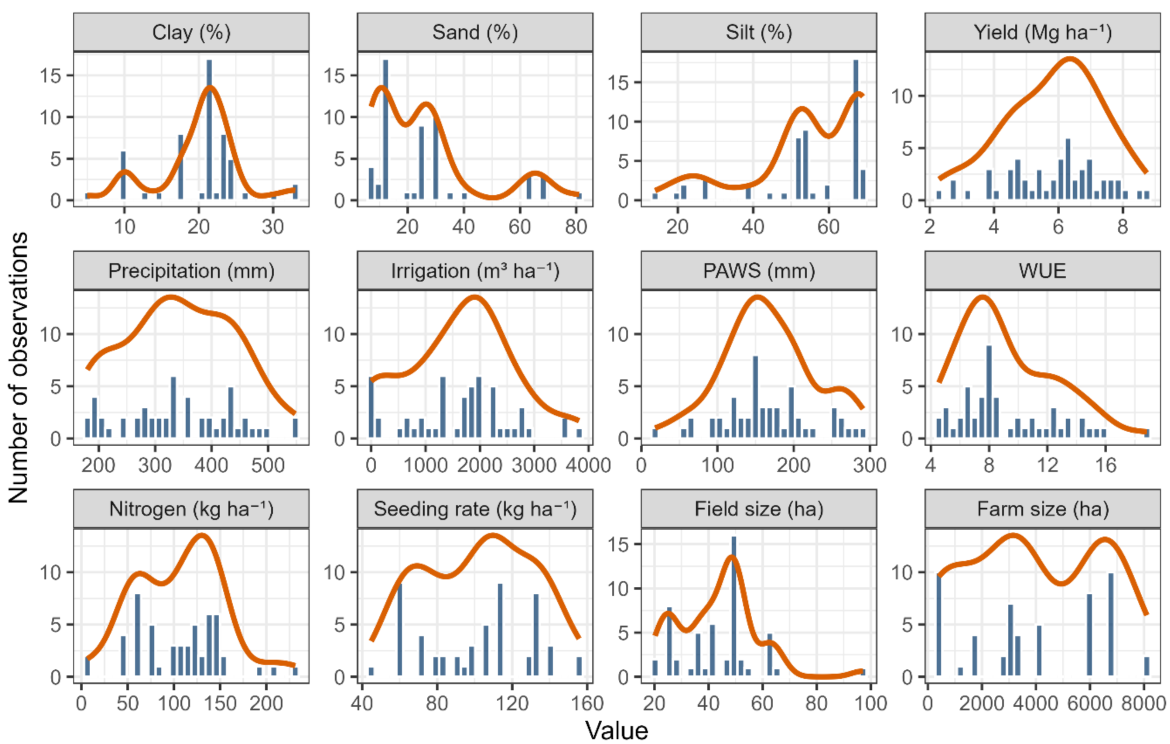

Figure 3.7 Histogram distributions for numeric variables of 53 surveyed irrigated wheat fields in Kansas. Bars depict the number of fields surveyed at each value of the variable, and the orange lines show the density curves.

3.3.2 Irrigated wheat sustainability under current and optimized management

To evaluate the sustainability of current irrigated wheat production, reported irrigation amounts and simulated irrigation requirements were compared with region-specific Irr Q-stable thresholds (Figure 3.8a). Under reported farmer management, 44 of 52 modeled fields (85%) remained below their respective sustainable irrigation limit. When irrigation was simulated to maximize yield potential without water limitations, only 35 fields (67%) remained below Irr Q-stable, indicating that increasing irrigation to eliminate yield gaps may reduce sustainability in some environments.

Increasing irrigation volume was not always required to improve yield. When the same seasonal irrigation amount reported by producers was redistributed according to simulated crop water demand, 22 of 52 fields (42%) increased yield by more than 5% solely through improved irrigation timing. The average yield improvement attributable to timing optimization was 1.08 Mg ha^{-1} (SD = 0.58) (Figure 3.8b). Furthermore, optimized irrigation timing allowed 36 fields to reach within 5% and 40 fields to reach within 10% of simulated yield potential without increasing seasonal irrigation volume.

3.3.3 Yield gap and water-use efficiency

Observed yields averaged 5.8 Mg ha^{-1} compared with simulated yield potential of 7.4 Mg ha^{-1}, resulting in an average yield gap of 1.6 Mg ha^{-1} (Figure 3.8c). Despite this yield gap, observed WUE was similar to simulated WUE under non-limiting conditions (Figure 3.8d), suggesting that differences in yield were not primarily caused by inefficient conversion of available water into grain, but rather by limitations in capturing yield potential.

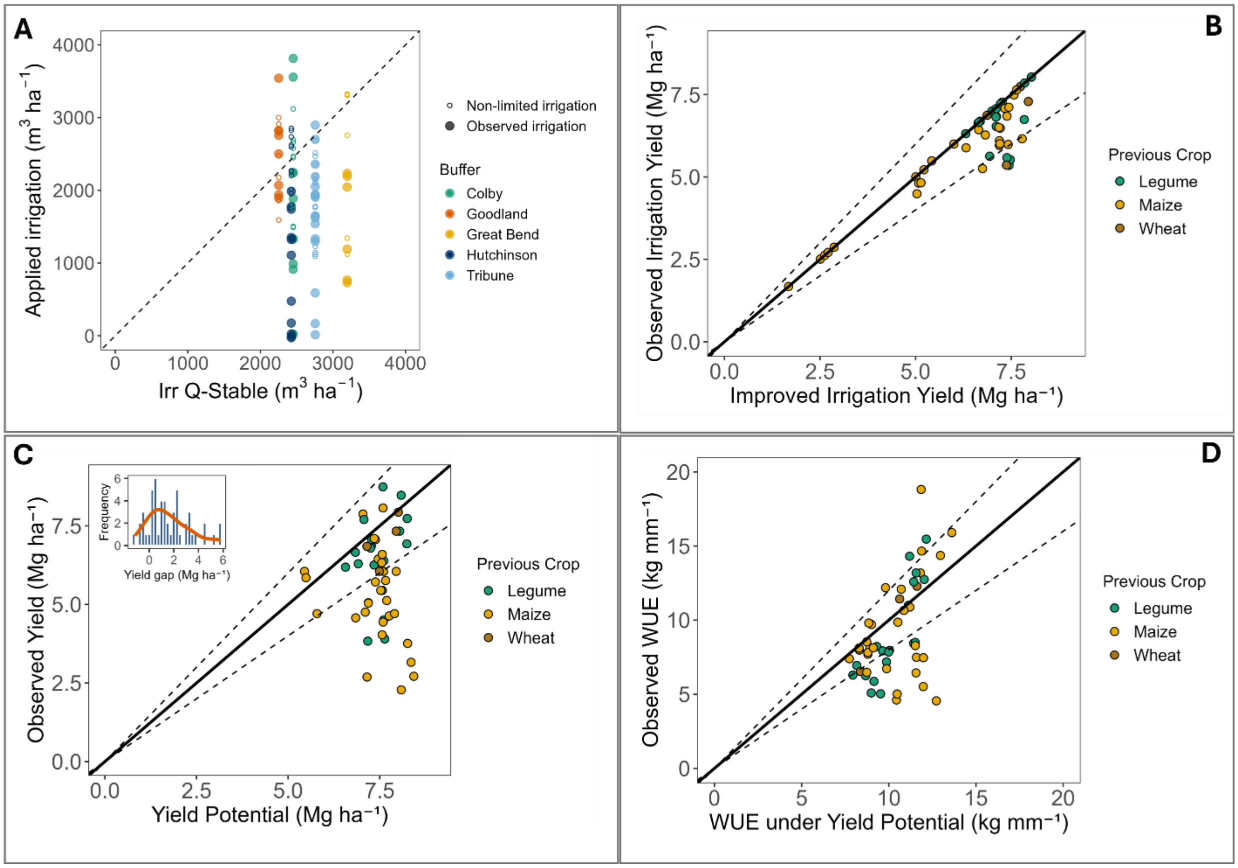

Figure 3.8 **(A)** Irrigation applied to each surveyed field under observed irrigation (filled circle) and non-limited irrigation (empty circle), compared to annual Irr Q-stable targets. Points above the dashed 1:1 line are over sustainable limits. Colors denote the geographic region that encompasses each surveyed field**.** **(B)** Comparison of yields reported in the farmer survey to the yields of those same fields simulated with the same maximum amount of irrigation, but improvements made to irrigation scheduling. **(C)** Observed yields reported by the farmer survey compared to simulated yield potential. Distribution of yield potentials is shown in the inset panel. **(D)** Observed water-use efficiency (WUE) compared to WUE under non-limited/yield potential irrigation and management. Dashed lines show 20% deviation from the one-to-one (solid) line for panels B, C, and D.

Total irrigation amount was compared between the observed and yield potential scenarios (Figure 3.8a). Only 12 of 52 fields need more than a 5% increase in applied irrigation to reach the irrigation volume of the yield potential scenario. In those fields, the average increase needed was 99.4 mm (SD = 50.86).

Minimal variation in growth stage allocation of irrigation existed between the observed and yield potential scenarios. The yield potential scenario exhibited a 5.8% (3.8-7.8% CI) increase in the proportion of total water applied during stem elongation, whereas the observed irrigation scenarios applied a slightly higher proportion of total water at seedling growth and tillering stages (-3.7% and -3.3%, respectively).

3.3.4 Factors influencing WUE

The Bayesian model used to evaluate whether observed producer management practices were associated with differences in WUE among surveyed fields had a moderate to strong performance (Bayesian $R^2 = 0.73$; 95% CI [0.50, 0.90]). All models exhibited good convergence ($\hat{R} < 1.01$ for all parameters), adequate effective sample sizes (> 1000), no divergent transitions, no saturated treedepths, and satisfactory Hamiltonian Monte Carlo energy diagnostics. Posterior predictive checks (density overlays and observed vs predicted plots) and posterior variance decomposition distributions are provided in Appendix Figure B.6.

For this analysis, surveyed fields were classified as western Kansas (n = 36) and central Kansas (n = 17). Bayesian variance decomposition indicated that measured covariates (management, soil, and field characteristics) accounted for approximately 28% of the total variation in WUE in the surveyed fields. Hierarchical random effects structure explained a substantial share of variability, with regional effects contributing approximately 24% and producer-level effects approximately 16%. Interannual variation was comparatively small (≈5%). The remaining 27% variation was attributed to residual unexplained variability (Appendix Figure B.7).

Although no individual predictors exhibited strong directional certainty across the full posterior (all 95% credible intervals overlapped zero), consistent trends in posterior sign probability were observed across the 53 surveyed fields, reflecting meaningful but uncertain associations within a limited spatial and temporal sampling domain (Figure 3.9). For categorical variables, the reference levels are as follows; fungicide and insecticide seed treatment, conventional tillage, and binary variables ‘no’.

Among management variables, zinc application showed the strongest positive directional signal ($Pr(\beta > 0) = 0.95$), followed by height of sprinkler system (0.93), field size (0.93), and later sowing date (0.90), suggesting consistently positive associations with WUE across posterior draws. Conversely, stronger negative directional tendencies were observed for soil and stress-related variables, including reported field damage ($Pr(\beta > 0) = 0.03$), sulfur application (0.12), and increased N rate (0.23), indicating a higher probability of negative associations with WUE. Field damage was reported by farmers as a percentage of their field that they felt had suffered yield losses for any reason such as hail damage, disease, pests, or machinery issues. Tillage system effects also showed moderate directional structure, with no-till and minimal tillage more likely associated with reduced WUE relative to conventional tillage, although uncertainty remained high. Given the modest sample size and restricted environmental gradient, results are best interpreted as indicative trends rather than definitive effects.

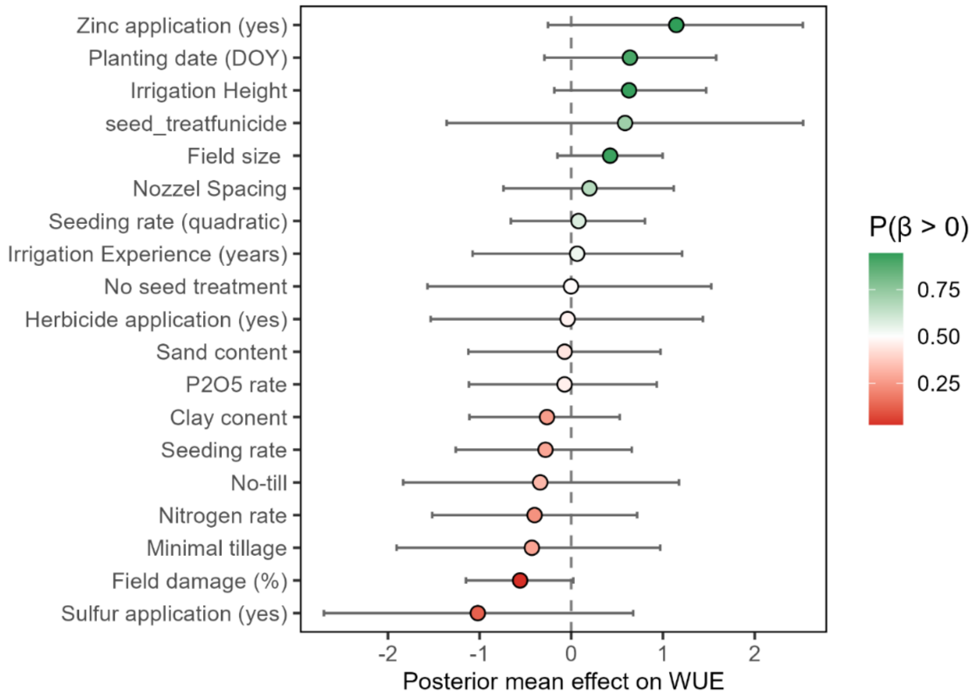

Figure 3.9 Posterior mean effects of agronomic and soil factors on water-use efficiency (WUE). Horizontal lines are the 95% confidence intervals for the effect sizes. Point color depicts the probability that each effect is directionally positive (green) or negative (red).

4. Discussion

This study integrates a regional water-balance analysis to define sustainable irrigation targets accounting for both agricultural and non-agricultural water usage, 30 years of crop modeling to evaluate crop choice under those constraints, and a farmer-reported management survey to identify opportunities for improving the water use efficiency of irrigated wheat. Together, these approaches demonstrate that crop selection is an opportunity to improve groundwater sustainability, while improved irrigation management and agronomic practices can further reduce water demand without compromising productivity.

4.1 Irr Q-stable as a sustainable irrigation target

Irr Q-stable provides a practical estimate of sustainable irrigation pumping that can be applied across diverse spatial contexts. Although Q-stable analysis was originally developed as a rapid assessment tool to evaluate aquifer-wide sustainability prospects, rather than crop-specific irrigation demand (Butler et al., 2016), adapting this framework to per-hectare irrigation by incorporating irrigated area, offers a scalable and intuitive benchmark for producers and policymakers that can be applied as a field-level target. Because Irr Q-stable is derived directly from long-term, point-based, water-balance records, it can be applied in any region with consistent water-use reporting. A key advantage of the Q-stable approach is that it does not rely on satellite remote sensing (Rodell & Famiglietti, 2002), complex numerical modeling based on stream inflow (Prudic, 1989), or hydraulic property parametrization (Butler et al., 2020b; Chen et al., 2005). Compared to the widely used array of process-based numerical models, Q-stable is less time and resource intensive, and can operate with relatively less data input, making it a better response too for water planners looking to quickly assess impacts of pumping reductions and set targets (Buchanan et al., 2015; Xiang et al., 2020).

The robustness of Irr Q-stable depends on two key assumptions: (1) net aquifer inflow remains stable over the analysis period, and (2) irrigation is the dominant water-use category. If municipal or industrial water use increases, or if recharge patterns shift, Irr Q-stable values should be recalculated to reflect new conditions (Butler et al., 2020a). Spatially, larger areas with denser measurement networks will produce more stable estimates. While in this research we calculated Irr Q-stable values at the region level, future applications should consider smoothing Irr Q-stable across geographic gradients to avoid abrupt transitions between adjacent regions.

This water-balance approach is not a substitute for numerical modeling; however, it is an easily understandable approach to complement hydrological modeling approaches (Butler et al., 2020b). Irr Q-stable serves as a sustainability threshold against which long-term crop water requirements can be evaluated, which in the current study was complemented by crop model simulations and farmer-reported irrigation practices.

4.2 Crop choice can improve aquifer sustainability

Reducing irrigation pumping can be achieved by shrinking irrigated area, improving irrigation efficiency, or selecting crops with lower water demand (Deines et al., 2019). However, these strategies do not provide equivalent opportunities, and each has associated tradeoffs. Shrinking or eliminating irrigated area seems a logical 'quick-fix' to reducing water-use. However, reductions to irrigated area are hard to achieve given the immense economic opportunities that irrigation creates on cropland. Suárez et al. (2018) estimated that the average net value of irrigation to be around 484$ USD per hectare annually in the High Plains Aquifer region. Improvements to irrigation efficiency are more realistic to adopt. Efficiency gains can be achieved with technology such as irrigation systems with lower evaporative losses or precise application using remote sensing (Bwambale et al., 2022; Mitchell-McCallister et al., 2020). These improvements can be costly and technical to implement (Pedersen et al., 2013). Crop genetics (Ritchie & Basso, 2008), and agronomic management (Liu et al., 2022; Ma et al., 2022; Sadras & Lawson, 2013) can also be used to improve water use efficiency. These improvements are ultimately constrained by crop physiology (Lollato et al., 2017; Grassini et al., 2011).

Meanwhile, crop selection as a tool to reduce irrigation water demand is a straightforward and easily adopted method to adapt management to water availability. Across the ten geographic regions, our results show that crop choice alone can shift production from unsustainable to sustainable irrigation levels. Continuous maize consistently exceeds Irr Q-stable, often requiring reductions greater than 50% to reach sustainable pumping in western regions such as Elkhart and Goodland. These levels are unlikely to be achieved through efficiency gains alone. This analysis did not explore the role of limited irrigation to meet these thresholds without majorly reducing yields. Deficit irrigation may offer a pathway to get closer to sustainability targets while possibly improving WUE and minimally impacting yields (Kresović et al., 2016; Yufeng et al., 2021). In contrast, wheat's substantially lower irrigation requirement allows it to remain below Irr Q-stable in nearly all regions and years.

Even under the most restrictive scenarios, wheat required reductions of approximately 8% as compared to a fully irrigated crop to consistently meet sustainability targets across all regions and five-year periods. These relatively small adjustments are within the range achievable through a combination of improved irrigation scheduling (Akbari et al., 2009), deficit irrigation (Yu et al., 2020; Daryanto et al., 2016), or improved agronomic management (Ma et al., 2025), suggesting that wheat provides a more realistic pathway toward groundwater sustainability than attempting to maintain high-water-demand cropping systems under severe pumping restrictions.

Across all regions, the sustainability threshold separated crop rotations into three distinct categories: continuous corn generally exceeded available groundwater budgets, wheat remained within sustainable limits, and maize–wheat rotations provided an intermediate strategy. This demonstrates that rotational diversification can reduce groundwater demand while maintaining irrigated production but also highlights that the magnitude of conservation achieved depends strongly on the proportion of low-water-demand crops included.

4.3 Economic implications of shifting crop rotations

Sustainability is not fully addressed without considering economic sustainability. Maize's higher profitability has historically driven declines in wheat acreage. In 2024, 1.3 million more acres were planted to wheat than maize in Kansas, yet corn's production value was twice as high (Schmall, 2025). However, under restricted irrigation, profitability must be evaluated within the constraints of available water. Wheat's lower water requirement and greater drought tolerance reduce yield risk when water is limited. Under 40% water reductions from non-limited irrigation, maize yields decline approximately 39% compared with 21% for wheat (Daryanto et al., 2016), and deficit irrigation studies have similarly shown smaller yield penalties and greater WUE improvements in wheat compared with maize (Liu et al., 2022). Thus, in water-limited environments, the economic tradeoff is not simply between high-yielding crops, but between crops that maximize production under unrestricted water and those that make efficient use of water in limited scenarios as well.

Including wheat in irrigated rotations can provide additional agronomic benefits. Wheat improves nitrogen use efficiency in maize–soybean systems (Gaudin et al., 2015a), can improve rotational productivity (Janovicek et al., 2021; Simão et al., 2024), and reduces weed pressure compared with continuous maize (Brankov et al., 2021). Wheat in rotation with soybean increased yield and yield stability compared to continuous soybeans (Simão et al., 2023; Gaudin et al., 2015b) Wheat also offers diverse management opportunities such as use as a grazed dual-purpose crop which can provide valuable forages during periods of the year when other forages are scarce (Simão et al., 2024). Additionally, reduced irrigation demand lowers pumping costs, which represent a substantial portion of irrigated crop production expenses in western Kansas (Pfeiffer & Lin, 2014). Therefore, crop choice influences both groundwater sustainability and the economic resilience of irrigated systems (Deines et al., 2019).

4.4 Closing the yield gap in surveyed irrigated wheat fields

The majority of fields surveyed applied irrigation volumes within 5% of the total amount needed to reach simulated yield potential. This indicates that many farmers are already fully irrigating their wheat. Yet a yield gap remains, suggesting that water management, not water volume, limits yield performance. Comparing using farmer irrigation scheduling and improved irrigation scheduling allows comparison of two scenarios where crops are agronomically managed to avoid all non-water stressors. Is it worth noting that in the fields that required increased irrigation volume to reach yield potential, closing yield gaps comes at a cost of reduced sustainability, an important trade-off to optimize (He et al., 2018).

Importantly, improvements in irrigation scheduling provided an opportunity to increase productivity without increasing irrigation volume. Approximately 42% of surveyed fields increased simulated yield by improving irrigation timing alone while maintaining the producer-reported seasonal irrigation amount. This finding complements the long-term sustainability analysis because wheat generally operates near or below Irr Q-stable limits; future improvements in irrigated wheat sustainability are unlikely to come primarily from large reductions in irrigation volume, but rather from improving the timing and effectiveness of limited water applications. Methods of decision used to determine the need for irrigation - evapotranspiration and water balance, soil moisture, plant water status, modeling – all perform with varying levels of accuracy to synchronize plant water demand with irrigation depending on soil type, environment, and crop (Gu et al., 2020; Ajaz et al., 2020). Investment in technology to monitor plant-available water and improve precipitation forecasting is necessary to maximize WUE, particularly when total water supply is limited (Cai et al., 2011).

4.5 Agronomic management as a tool for improved WUE

Unlike the irrigation timing simulations, which isolate the effect of water management under controlled modeling assumptions, this analysis evaluates associations among farmer-reported practices and observed WUE. Therefore, results should be interpreted as exploratory indicators of management strategies rather than direct recommendations.

Zinc (Zn) application showed the strongest positive directional association with WUE. Wheat Zn deficiency is uncommon in the U.S. Great Plains (Miner et al., 2020; Widmar, 2013); however, zinc is commonly applied in maize–wheat rotations to support maize yield, which is sensitive to zinc deficiency (Stewart et al., 2021; Suganya et al., 2020). As a result, zinc use may act as a proxy for more intensively managed fields, where producers invest in nutrient programs, timely operations, and overall management precision. These same fields may also exhibit better irrigation scheduling, residue management, or soil fertility, factors that indirectly improve WUE in wheat. Thus, the observed zinc–WUE relationship likely reflects management intensity or rotation context, rather than a physiological zinc response in wheat.

Field size also trended positively with WUE. Larger fields may indicate farms with greater access to labor, technology, or capital, which can translate into more optimized irrigation and nutrient management. Sowing date showed a modest positive trend as well. Some studies report improved WUE with earlier sowing (Hochman et al., 2009; Duchemin et al., 2015), while others found no significant effect (Chen et al., 2003; Vashisht et al., 2019). These conflicting results likely reflect regional environmental differences, and the weak directional trend observed here should be interpreted cautiously.

Sulfur application showed a negative directional association with WUE. Because most fields reported sulfur applications, this pattern may be driven by a small number of high-WUE fields without sulfur rather than a true agronomic effect, especially as sulfur deficiency is common in wheat production in this region (Jaenisch et al., 2026). Field damage behaved as expected: increased damage reduced yields and therefore reduced WUE, underscoring the importance of accounting for non-management stressors in survey-based datasets.

Water use efficiency can be influenced by genetic factors (Ritchie & Basso, 2008; Sadra & Angus, 2006), which were not explored in this analysis. Practices such as residue management and seeding rate are known to affect WUE (Liu et al., 2022; Ma et al., 2022; Sadras & Lawson, 2013), but the limited range of management variation in the surveyed fields likely prevented these effects from emerging in our analysis. Future research combining larger producer datasets, replicated field experiments, and detailed irrigation monitoring will be necessary to distinguish management practices that truly increase wheat.

4.6 Implications for future conservation policy

This research highlights the role of crop choice and proper crop management in stabilizing aquifer water levels for long-term agricultural sustainability. The Sheridan 6 LEMA, established in northwest Kansas in 2012, demonstrated that groundwater levels can be stabilized through reductions in irrigation depth (primarily in maize) and shifts toward less water-intensive crops such as wheat and sorghum. Changes in crop choice alone accounted for 19% of total water-use reductions in the LEMA (Deines et al., 2019), all achieved with minimal reductions in irrigated area.

Our findings reinforce this outcome. Wheat's lower irrigation requirement, greater drought tolerance, and rotational benefits position it as a key crop for sustaining agricultural production under declining groundwater availability. Annual reporting on the status of the High Plains aquifer has incorporated q-stable analysis at a groundwater management district (GMD) scale in recent years. Whittemore et al. (2023) reported comparable q-stable values to this analysis (when comparing like regions) and necessary reductions to total pumping upwards of 32% based on 2009-2022 data.

By combining a scalable water-balance metric, long-term crop modeling, and farmer-reported management, this study provides realistic and attainable support for designing conservation strategies that maintain productivity while reducing pressure on the High Plains Aquifer.

4.7 Study limitations

Long-term crop simulations were considered fully irrigated, defined by maintaining the plant-available water profile 50-90% full. However, water demand fluctuates throughout the season, peaks around grain-filling, and rapidly drops off as the plant approaches maturity (Irmak et al., 2016). Maize water demand similarly drops off as leaves begin to senesce (Trout & DeJonge, 2018). Due to the varied water demands throughout the season, the model may in some cases slightly overestimate the irrigation requirements by continuing to maintain consistent irrigation thresholds through the end of the season. In addition the trigger depths for irrigation we fixed for both wheat and maize, not reflective of the true root zone of the crops at earlier growth stages. These behaviors may minimally impact total irrigation quantities, but the relationships between crop rotations are not impaired. This threshold-based method for triggering irrigation may also explain why the seasonal water supplies for both wheat and maize are simulated higher than the water supplies estimated to maximize yields reported in the literature of around 450 mm for wheat and 900 mm for maize (Grassini et al., 2011; Moghbel et al., 2024; French & Schultz, 1984; Patrignani et al., 2014; Lollato et al., 2017). Similarly, the model methodology driving the storage of water between crops dictates available water at sowing. These simulations found minimal differences in water demand of maize following wheat or maize following maize. Previous work has shown that maize following wheat benefits from a higher plant-available water at sowing due to greater off-season water accumulation in the months following wheat harvest, as opposed to a previous summer crop (Schlegel et al., 2019).

Another limitation of our analysis is that it was limited to full irrigated wheat and maize production, while there are other crops that farmers and researchers are already exploring as options to reduce their water demands, such as high-quality forages for dairy cattle, grain sorghum, triticale, and pearl millet (Devlin & Minton, 2018). Additionally, producer surveys revealed that irrigated rotations in Kansas also included crops other than corn and wheat, particularly soybean and dry bean. These crops may influence future irrigation sustainability decisions because their water requirements fall between or below those of maize and wheat. Soybeans need around 650 mm of total seasonal water supply to reach yield potential in Nebraska (Grassini et al., 2015), which places it between wheat and maize requirements. Dry beans may require as little as 400 mm or less of total water supply in the US Great Plains (Yonts, 2006; Nielsen, 2018), making them the least water-demanding crop discussed here. However, dry beans' shallow rooting depth and short season limit their ability to access deep soil moisture, requiring irrigation to maintain moisture in the top 60 cm of the soil profile (Alberta Agriculture and Forestry, 2011).

These crops were not included in the long-term DSSAT simulations due to a lack of accurately calibrated models. Further work on both legumes is warranted to understand the pressure they place on the aquifer.

Although planting dates used to simulate wheat after maize were representative of the surveyed fields, the simulations did not account for the impact the preceding crop may have on wheat stand establishment. Impaired plant emergence in no-till maize-wheat systems leads to lower yields compared to conventional and minimal till systems (Barut et al., 2010). For more accurate modeling, future analysis should consider the impact of previous crop residue on wheat establishment and subsequent yields.

There are also limitations associated with the survey component of this study. The survey was not intended to independently estimate regional sustainability, but rather to characterize current management practices and identify opportunities for improving water use efficiency within the sustainability framework established through crop modeling. Farmer surveys offer a unique opportunity to glimpse real-world management practices at scale. However, this approach also introduces limitations not present in traditional plot-scale research. In this study, a relatively small number of responses were collected, which restricts the strength of inference that can be made. For example, Mourtzinis et al. (2018) suggested that a minimum of about 100 responses were needed for proper statistical power in a survey performed with soybean yield and management in the US Corn Belt. While we acknowledge that more responses would be preferred, crop modeling allows us to still gain field-level inference from the dataset on irrigation practices. The limited dataset does make it difficult to have statistical power behind more traditional modeling approaches. Therefore, the survey is most reliably viewed as a qualitative assessment of where current practices lie. Because individual farmers reported anywhere from one to ten fields, all analysis is inherently confounded by the influence of the reporting farmer. Fields managed by the same farmer are more likely to be geographically clustered and managed similarly, in contrast to fields reported by different farmers. This clustering reduces independence among observations and may mask variation in management practices that exists across the broader irrigated wheat-growing region.

Additionally, some farmers provided detailed and precise information, while others reported more general estimates, contributing to variability in the reliability of field-level data. Despite these limitations, the survey provides a look at an otherwise minimally studied cropping system in Kansas irrigated wheat. These responses serve as the foundation for understanding current practices and identifying management trends that can guide future research. For example, the characterization of irrigated wheat in this database could serve as a background benchmark for future field research to test technologies against (e.g., Andrade et al., 2022).

Conclusions

This study introduced Irr Q-stable, a scalable irrigation sustainability metric that translates aquifer-level water balance principles into region-level irrigation targets. When combined with 30 years of crop modeling, Irr Q-stable demonstrated that crop choice is a primary driver of groundwater sustainability. Continuous maize frequently exceeded sustainable irrigation limits, with required reductions in some western Kansas regions too large to be achieved through irrigation efficiency improvements alone. In contrast, wheat remained within sustainable irrigation limits across nearly all regions and periods, while maize–wheat rotations provided an intermediate pathway for reducing groundwater demand without eliminating irrigated production.

Wheat is not only a lower-water crop choice, it is also a crop where existing production systems are already close to sustainable irrigation limits, and further improvements are more likely to come from management efficiency rather than additional water inputs. Survey-based simulations showed that 42% of irrigated wheat fields could increase yield through improved irrigation timing while maintaining current irrigation volumes, demonstrating an opportunity to increase productivity without increasing groundwater use. Wheat can be integrated into existing systems to build flexible, diverse, and sustainable operations. Observed management trends further suggest that improved nutrient management and overall management intensity may contribute to greater water-use efficiency, although additional research is needed to validate these relationships.

Together, the integration of sustainability targets, long-term crop simulations, and producer management data provides a framework for identifying cropping systems that maintain agricultural productivity while reducing pressure on the High Plains Aquifer. This work highlights irrigated wheat as a key component of sustainable groundwater management and provides direction for future efforts to optimize wheat production under increasingly limited water availability.

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Chapter 4 - Conclusions and Future Research

This thesis evaluated two contrasting wheat production systems in Kansas, dual-purpose wheat and irrigated wheat, to inform productive and sustainable management recommendations. Although these systems differ in their management objectives, both studies demonstrate that meaningful gains can be achieved through realistic management adaptations rather than increased resource inputs.

The first study demonstrated that current grazing termination recommendations for dual-purpose wheat are not sufficiently conservative to prevent grain yield loss. A review of the literature found little evidence supporting the commonly recommended 1.5 cm hollow stem threshold, while analysis of nine years of field data identified approximately 0.60 cm as the point beyond which defoliation reduces grain yield. Beyond this threshold, additional forage production rarely compensated for the economic value of lost grain under realistic market conditions. These findings support revising current recommendations to terminate grazing at or before the first visible hollow stem when maintaining grain yield potential is the primary objective.

The second study introduced Irr Q-stable as a novel framework for translating aquifer water-balance relationships into irrigation sustainability targets that can be directly compared with crop water requirements. Long-term crop simulations demonstrated that crop choice is a primary driver of irrigation sustainability. Irrigated wheat consistently required substantially less irrigation than corn and remained within sustainable pumping limits across regions and years, even under fully irrigated conditions. Farmer survey data further showed that many irrigated wheat fields already apply irrigation volumes close to those required to achieve simulated yield potential, indicating that the greatest opportunities for increasing productivity lie in improved irrigation scheduling and agronomic management rather than additional groundwater pumping. These findings further reinforce the value of irrigated wheat in maintaining aquifer longevity.

Several opportunities exist to build on this research. For dual-purpose wheat, additional field experiments comparing simulated defoliation with cattle grazing across multiple environments would strengthen confidence in revised grazing recommendations by accounting for selective grazing, trampling, and plant uprooting. Economic analyses should also incorporate the full costs associated with grain-only and dual-purpose systems, including fertilizer and labor requirements, to better quantify the profitability of forage and grain production under varying conditions.

The second study highlights the need for Great Plains-based, irrigated wheat research. Controlled field experiments and larger producer datasets are needed to identify agronomic practices that maximize water-use efficiency while conserving groundwater resources. Further work on irrigation scheduling, deficit irrigation strategies, and producer-accessible decision support tools will help refine irrigation management under increasing water limitations. Continued improvements in wheat productivity and profitability will also be necessary to maintain wheat as a competitive alternative to corn in regions where continuous corn is not sustainable. Finally, future research should quantify the potential gains in water-use efficiency from both genetic improvement and management advances across wheat, corn, and alternative crops. Although future technological advances may alter the relative sustainability of different cropping systems, the irrigation reductions currently required for continuous corn in many regions remain too large to be achieved through management improvements alone, making wheat the more sustainable option under present conditions.

Together, these studies demonstrate that, given wheat's importance to Kansas agriculture, research must encompass the diversity of wheat production systems to ensure producers have access to evidence-based management recommendations. By integrating literature review, field experiments, producer surveys, and crop modeling, this thesis shows that whether managed as a dual-purpose crop or an irrigated grain crop, opportunities exist to improve wheat productivity, profitability, and sustainability through informed management.

References

Abou Rayya, M., Karrou, M., & Oweis, T. (2011). Water use efficiency and water productivity of wheat under supplemental irrigation in a Mediterranean environment. African Journal of Agricultural Research, 6(15), 3569–3576.

Ajaz, A., Datta, S., & Stoodley, S. (2020). High Plains Aquifer–State of Affairs of Irrigated Agriculture and Role of Irrigation in the Sustainability Paradigm. *Sustainability*, *12*(9), 3714. https://doi.org/10.3390/su12093714

Akbari, M., Dehghani Sanij, H., & Mirlatifi, S. M. (2009). Impact of irrigation scheduling on agriculture water productivity. Iranian Journal of Irrigation and Drainage, 3(1), 69–79.

Alberta Agriculture and Rural Development. (2011, December). *Irrigation scheduling for dry bean in southern Alberta* (Agdex 142/561-1). Government of Alberta. https://WWw1.agriculture.alberta.ca/$department/deptdocs.nsf/all/agdex13368/$file/142_561-1.pdf

Alharbi, S., Felemban, A., Abdelrahim, A., & Al-Dakhil, M. (2024). Agricultural and technology-based strategies to improve water-use efficiency in arid and semiarid areas. *Water, 16*(13), 1842. https://doi.org/10.3390/w16131842

Allen, E. M. (1996). *Verification of models to predict soybean and corn growth in Iowa* (Master's thesis). Iowa State University Digital Repository.

Andrade, J. F., Mourtzinis, S., Edreira, J. I. R., Conley, S. P., Gaska, J., Kandel, H. J., Lindsey, L. E., Naeve, S., Nelson, S., Singh, M. P., & Thompson, L. (2022). Field validation of a farmer-supplied data approach to close soybean yield gaps in the US North Central region. Agricultural Systems, 200, 103434. https://doi.org/10.1016/j.agsy.2022.103434

Araya, A., Prasad, P. V. V., Gowda, P. H., Sharda, V., Rice, C. W., & Ciampitti, I. A. (2021). Evaluating optimal irrigation strategies for maize in western Kansas. *Agricultural Water Management, 246*, Article 106677. https://doi.org/10.1016/j.agwat.2020.106677

Awika, J. (2011). Major cereal grains production and use around the world. In J. Awika, V. Piironen, & S. Bean (Eds.), Advances in cereal science: Implications to food processing and health promotion (pp. 1–13). American Chemical Society.

Barut, Z. B., & Çelik, I. (2010). Different tillage systems affect plant emergence, stand establishment and yield in wheat-corn rotation. *The Philippine Agricultural Scientist, 93*(4), 392–398.

Bell, L. W., Moore, A. D., & Kirkegaard, J. A. (2014). Evolution in crop–livestock integration systems that improve farm productivity and environmental performance in Australia. Crop and Pasture Science, 64(6), 556–568. https://doi.org/10.1071/CP13051

Bidinger, F., Musgrave, R., & Fischer, R. (1977). Contribution of stored pre-anthesis assimilate to grain yield in wheat and barley. Nature, 270, 431–433. https://doi.org/10.1038/270431a0

Blümmel, M., Duncan, A. J., & Lenné, J. M. (2020). Recent advances in dual purpose rice and wheat research: A synthesis. Field Crops Research, 253, 107823. https://doi.org/10.1016/j.fcr.2020.107823

Bohling, G. C., & Wilson, B. B. (2012). *Statistical and geostatistical analysis of the Kansas High Plains water-table elevations, 2012 measurement campaign* (Open File Report 2012-16). Kansas Geological Survey. https://WWw.kgs.ku.edu/Hydro/Publications/2012/OFR12_16/index.html

Brankov, M., Simić, M., & Dragičević, V. (2021). The influence of maize–winter wheat rotation and pre-emergence herbicides on weeds and maize productivity. *Crop Protection, 143*, Article 105558. https://doi.org/10.1016/j.cropro.2021.105558

Brock, F. V., et al., 1995: "The Oklahoma Mesonet: A technical overview" J. Atmos. Oceanic Technol. 12, 5-19.

Buchanan, R. C., Wilson, B. B., & Butler, J. J., Jr. (2023). High Plains aquifer (Originally published 2001; revised January 2023). Kansas Geological Survey. https://kgs.ku.edu/high-plains-aquifer

Butchee, J. D., & Edwards, J. T. (2013). Dual-purpose wheat grain yield as affected by growth habit and simulated grazing intensity. Crop Science, 53(4), 1686–1692. https://doi.org/10.2135/cropsci2013.01.0033

Butler, J. J., Jr., Bohling, G. C., Whittemore, D. O., & Wilson, B. B. (2016). A new approach for assessing the future of aquifers supporting irrigated agriculture. *Geophysical Research Letters, 43*(5), 2004–2010. https://doi.org/10.1002/2016GL067879

Butler, J. J., Jr., Bohling, G. C., Whittemore, D. O., & Wilson, B. B. (2020a). Charting pathways toward sustainability for aquifers supporting irrigated agriculture. *Water Resources Research, 56*(10), Article e2020WR027961. https://doi.org/10.1029/2020WR027961

Butler, J. J., Jr., Bohling, G. C., Whittemore, D. O., & Wilson, B. B. (2020b). A roadblock on the path to aquifer sustainability: Underestimating the impact of pumping reductions. *Environmental Research Letters, 15*(1), Article 014003. https://doi.org/10.1088/1748-9326/ab6002

Bwambale, E., Abagale, F. K., & Anornu, G. K. (2022). Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. *Agricultural Water Management, 260*, 107324. https://doi.org/10.1016/j.agwat.2021.107324

Cai, X., Hejazi, M. I., & Wang, D. (2011). Value of probabilistic weather forecasts: Assessment by real-time optimization of irrigation scheduling. *Journal of Water Resources Planning and Management, 137*(5), 391–403. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000126

Changlu Hu, Sadras, V. O., Lu, G., Jin, X., Xu, J., Ye, Y., Yang, X., & Zhang, S. (2019). Dual-purpose winter wheat: Interactions between crop management, availability of nitrogen and weather conditions. Field Crops Research, 241, 107579. https://doi.org/10.1016/j.fcr.2019.107579

Chen, C., Payne, W. A., Smiley, R. W., & Stoltz, M. A. (2003). Yield and water-use efficiency of eight wheat cultivars planted on seven dates in northeastern Oregon. *Agronomy Journal, 95*, 836–843. https://doi.org/10.2134/agronj2003.836

Chen, X., Yin, Y., Goeke, J. W., et al. (2005). Vertical movement of water in a High Plains aquifer induced by a pumping well. *Environmental Geology, 47*, 931–941. https://doi.org/10.1007/s00254-005-1223-4

Daryanto, S., Wang, L., & Jacinthe, P.-A. (2016). Global synthesis of drought effects on maize and wheat production. *PLOS ONE, 11*(5), Article e0156362. https://doi.org/10.1371/journal.pone.0156362

Deines, J. M., Kendall, A. D., Butler, J. J., Jr., & Hyndman, D. W. (2019). Quantifying irrigation adaptation strategies in response to stakeholder-driven groundwater management in the US High Plains Aquifer. *Environmental Research Letters, 14*(4), Article 044014. https://doi.org/10.1088/1748-9326/aafe39

Devlin, D. L., & Minton, J. E. (2018, March 20). *KSU Research and Extension programs on water to sustain the economy of western Kansas*. Testimony presented to the House Committee on Water & Environment, Kansas Legislature. https://WWw.kslegislature.gov/li_2018/b2017_18/committees/ctte_h_water_and_environment_1/documents/testimony/20180320_02.pdf

Dove, H., Holst, P. J., Stanley, D. F., & Flint, P. W. (2002). Grazing value of dual-purpose winter wheats for young sheep. Animal Production in Australia, 24, 53–56.

Duchemin, B., Fieuzal, R., Rivera, M. A., Ezzahar, J., Jarlan, L., Rodriguez, J. C., Hagolle, O., & Watts, C. (2015). Impact of sowing date on yield and water use efficiency of wheat analyzed through spatial modeling and FORMOSAT-2 images. *Remote Sensing, 7*(5), 5951–5979. https://doi.org/10.3390/rs70505951

Dunphy, D. J., McDaniel, M. E., & Holt, E. C. (1982). Effect of forage utilization on wheat grain yield. Crop Science, 22(1), 106–109. https://doi.org/10.2135/cropsci1982.0011183X002200010024x

Edwards, J. T., & Horn, G. W. (2016). First hollow stem: A critical wheat growth stage for dual-purpose producers. Crops & Soils, 49(1), 10–14.

Edwards, J. T., Carver, B. F., & Payton, M. E. (2007). Relationship of first hollow stem and heading in winter wheat. Crop Science, 47(5), 2074–2077. https://doi.org/10.2135/cropsci2007.01.0057sc

Edwards, J. T., Carver, B. F., Horn, G. W., & Payton, M. E. (2011). Impact of dual purpose management on wheat grain yield. Crop Science, 51

Epplin, F. M., Hossain, I., & Krenzer, E. G., Jr. (2000). Winter wheat fall–winter forage yield and grain yield response to planting date in a dual-purpose system. Agricultural Systems, 63(3), 161–173. https://doi.org/10.1016/S0308-521X(00)00004-4 FAOSTAT. (2026). Food and Agriculture Organization of the United Nations statistical database. https://www.fao.org/faostat/en/

Erenstein, O., Jaleta, M., Mottaleb, K. A., Sonder, K., Donovan, J., & Braun, H. J. (2022). Global trends in wheat production, consumption and trade. In M. P. Reynolds & H. J. Braun (Eds.), Wheat improvement. Springer. https://doi.org/10.1007/978-3-030-90673-3_4

Federico García Suárez, F., Fulginiti, L. E., & Perrin, R. K. (2019). What is the use value of irrigation water from the High Plains aquifer? *American Journal of Agricultural Economics, 101*(2), 455–466. https://doi.org/10.1093/ajae/aay062

Fieser, B. G., Horn, G. W., & Krenzer, E. G., Jr. (2006a). Effects of planting date and forage allowance on steer growth performance and grain yield in a dual-purpose winter wheat system. The Professional Animal Scientist, 22, 424–431.

Fieser, B.G., G.W. Horn, J.T. Edwards, and E.G. Krenzer, Jr. (2006b) ‘‘Timing of Grazing Termination in Dual-Purpose Winter Wheat Enterprises.’’ The Professional Animal Scientist 22: 210–16.

French, R., & Schultz, J. (1984). Water use efficiency of wheat in a Mediterranean-type environment. II. Some limitations to efficiency. *Australian Journal of Agricultural Research, 35*, 765. https://doi.org/10.1071/AR9840765

Gaudin, A. C. M., Janovicek, K., Deen, B., & Hooker, D. C. (2015a). Wheat improves nitrogen use efficiency of maize and soybean-based cropping systems. *Agriculture, Ecosystems & Environment, 210*, 1–10. https://doi.org/10.1016/j.agee.2015.04.034

Gaudin, A. C. M., Tolhurst, T. N., Ker, A. P., Janovicek, K., Tortora, C., Martin, R. C., & Deen, W. (2015). Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS ONE, 10*(2), e0113261. https://doi.org/10.1371/journal.pone.0113261

Grassini, P., Eskridge, K. M., & Cassman, K. G. (2013). Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature Communications, 4*, 2918. https://doi.org/10.1038/ncomms3918

Grassini, P., Torrion, J. A., Yang, H. S., Rees, J., Andersen, D., Cassman, K. G., & Specht, J. E. (2015). Soybean yield gaps and water productivity in the western U.S. Corn Belt. *Field Crops Research, 179*, 150–163. https://doi.org/10.1016/j.fcr.2015.05.023

Grassini, P., Yang, H., Irmak, S., Thorburn, J., Burr, C., & Cassman, K. G. (2011). High-yield irrigated maize in the Western U.S. Corn Belt: II. Irrigation management and crop water productivity. *Field Crops Research, 120*(1), 133–141. https://doi.org/10.1016/j.fcr.2010.09.013

Gu, Z., Qi, Z., Burghate, R., Yuan, S., Jiao, X., & Xu, J. (2020). Irrigation scheduling approaches and applications: A review. *Journal of Irrigation and Drainage Engineering, 146*(6), Article 04020007. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001464

Han, E., Kirkegaard, J. A., & Thorup Kristensen, K. (2024). Temporary growth cessation of wheat roots following defoliation. Plant and Soil, 502, 315–331.

Han, E., Whish, J., Li, X., Swan, T., Lilley, J., Thorup-Kristensen, K., & Kirkegaard, J. A. (2026). Root development and water availability in dual-purpose wheat. Field Crops Research, 342, 110444. https://doi.org/10.1016/j.fcr.2026.110444

Harrison MT, Evans JR, Dove H, Moore AD. (2011) Dual-purpose cereals: can the relative influences of management and environment on crop recovery and grain yield be dissected?. Crop & Pasture Science 62, 930–946. https://doi.org/10.1071/CP11066

He, G., Cui, Z., Ying, H., Zheng, H., Wang, Z., & Zhang, F. (2018). Managing the trade-offs among yield increase, water resources inputs and greenhouse gas emissions in irrigated wheat production systems. *Journal of Cleaner Production, 188*, 72–81. https://doi.org/10.1016/j.jclepro.2017.06.085

Hochman, Z., Holzworth, D., & Hunt, J. R. (2009). Potential to improve on-farm wheat yield and WUE in Australia. *Crop & Pasture Science, 60*, 708–716. https://doi.org/10.1071/CP09064

Holman, J. D., Lollato, R. P., Marburger, D., Tomlinson, P., Presley, D., & Edwards, J. T. (2017). Dual-purpose wheat: Management for forage and grain production (PSS-2178). Oklahoma State University Extension. https://extension.okstate.edu/fact-sheets/dual-purpose-wheat-management-for-forage-and-grain-production.html

Holman, J. D., Obour, A. K., O'Brien, D., Prasad, P. V. V., & Assefa, Y. (2024). Historic corn yield, production, and economic value trends in Kansas. *Agronomy Journal, 116*, 1428–1439. https://doi.org/10.1002/agj2.21557

IFPRI; International Food Policy Research Institute. (2019). *Global spatially-disaggregated crop production statistics data for 2010 (Version 2.0).* https://doi.org/10.7910/DVN/PRFF8V

Irmak, S., Sharma, V., & Djaman, K. (2016). *Winter wheat (Triticum aestivum L.) evapotranspiration (crop water use) and crop coefficients* (Extension Circular EC3005). University of Nebraska Extension.

Jaenisch, B.R., Giordano, N., Sadras, V.O., Nelson, N.O., Guttieri, M.J., Fritz, A.K., Diaz, D.R. and Lollato, R.P., 2026. Nitrogen and sulfur co-limitation and stoichiometry modulate yield and nutrient use efficiency of bread wheat. *Field Crops Research*, *344*, p.110539.

Jaenisch, B.R., Munaro, L.B., Bastos, L.M., Moraes, M., Lin, X. and Lollato, R.P., 2021. On-farm data-rich analysis explains yield and quantifies yield gaps of winter wheat in the US central Great Plains. Field Crops Research, 272, p.108287.

Janovicek, K., Hooker, D., Weersink, A., & Vyn, R., & Deen, B. (2021). Corn and soybean yields and returns are greater in rotations with wheat. *Agronomy Journal, 113*, 1691–1711. https://doi.org/10.1002/agj2.20605

Jones, C. A., & Kiniry, J. R. (Eds.). (1986). *CERES-Maize: A simulation model of maize growth and development*. Texas A&M University Press.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., & Ritchie, J. T. (2003). The DSSAT cropping system model. *European Journal of Agronomy, 18*(3–4), 235–265. https://doi.org/10.1016/S1161-0301(02)00107-7

Kansas Department of Agriculture. (2025). *2025 Economic Contribution Report*. Office of the Economist, Kansas Department of Agriculture.

Kansas Geological Survey. (n.d.). *Water Information Storage and Retrieval Database (WIZARD)* [Data set]. Retrieved July 2026, from https://WWw.kgs.ku.edu/Magellan/WaterLevels/

Kansas Mesonet, 2026: Kansas Mesonet Historical Data. Kansas State University. Accessed January 22, 2026, k-state.edu.

Kelman WM, Dove H. (2009) Growth and phenology of winter wheat and oats in a dual-purpose management system. Crop & Pasture Science 60, 921–932. https://doi.org/10.1071/CP09029

Khalid, A., Hameed, A., & Tahir, M. F. (2023). Wheat quality: A review on chemical composition, nutritional attributes, grain anatomy, types, classification, and function of seed storage proteins in bread making quality. Frontiers in Nutrition, 10, 1053196. https://doi.org/10.3389/fnut.2023.1053196

Khalil, S. K., Khan, F., Rehman, A., Muhammad, F., Amanullah, Khan, A. Z., Wahab, S., Akhtar, S., Zubair, M., Khalil, I. H., Shah, M. K., & Khan, H. (2011). Dual purpose wheat for forage and grain yield in response to cutting, seed rate and nitrogen. Pakistan Journal of Botany, 43(2), 937–947.

Kirkegaard JA, Sprague SJ, Hamblin PJ, Graham JM, Lilley JM. (2012) Refining crop and livestock management for dual-purpose spring canola (Brassica napus). Crop & Pasture Science 63, 429–443. https://doi.org/10.1071/CP12163

Kirkegaard, J. A., Lilley, J. M., Hunt, J. R., Sprague, S. J., Ytting, N. K., Rasmussen, I. S., & Graham, J. M. (2015). Effect of defoliation by grazing or shoot removal on the root growth of field-grown wheat (Triticum aestivum L.). Crop & Pasture Science, 66(4), 300–315. https://doi.org/10.1071/CP14082

Kirkegaard, J., Sprague, S., Lilley, J., Bell, L., & Swan, T. (2019, February 28). Maximising systems benefits from dual purpose crops: Early sowing and grazing strategies. Grains Research and Development Corporation. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/maximising-systems-benefits-from-dual-purpose-crops-early-sowing-and-grazing-strategies

Kresović, B., Tapanarova, A., Tomić, Z., Životić, L., Vujović, D., Sredojević, Z., & Gajić, B. (2016). Grain yield and water use efficiency of maize as influenced by different irrigation regimes through sprinkler irrigation under temperate climate. *Agricultural Water Management, 169*, 34–43. https://doi.org/10.1016/j.agwat.2016.01.023

Large, E.C. (1954). "Growth Stages in Cereals: Illustration of the Feekes Scale." Plant Pathology.

Liu, B. Y., Liu, W. S., Lin, B. J., et al. (2022). Sustainable management practices to improve the water use efficiency of winter wheat in the North China Plain: A meta-analysis. *Agronomy for Sustainable Development, 42*, Article 33. https://doi.org/10.1007/s13593-022-00766-8

Lollato, R. P., & Edwards, J. T. (2015). Maximum attainable wheat yield and resource-use efficiency in the Southern Great Plains. *Crop Science, 55*(6), 2863–2876. https://doi.org/10.2135/cropsci2015.04.0215

Lollato, R. P., Bavia, G. P., Perin, V., Knapp, M., Santos, E. A., Patrignani, A., & DeWolf, E. D. (2020). Climate-risk assessment for winter wheat using long-term weather data. Agronomy Journal, 112, 2132–2151. https://doi.org/10.1002/agj2.20168

Lollato, R. P., Beres, B. L., Romero Soler, J. A., Andrade, J. F., Giordano, N., Wang, Z., Couëdel, A., PileCCo, I., Aramburu-Merlos, F., & Grassini, P. (2026). Intensifying wheat production in North America to ensure a stable global wheat supply [Unpublished manuscript].

Lollato, R. P., Edwards, J. T., & Ochsner, T. E. (2017). Meteorological limits to winter wheat productivity in the U.S. southern Great Plains. *Field Crops Research, 203*, 212–226. https://doi.org/10.1016/j.fcr.2016.12.014

Lollato, R. P., Marburger, D., Holman, J. D., Tomlinson, P., Presley, D., & Edwards, J. T. (2017). Dual-purpose wheat: Management for forage and grain production (MF3375). Kansas State University Agricultural Experiment Station and Cooperative Extension Service.

Lollato, R. P., Patrignani, A., Ochsner, T., Rocateli, A., Tomlinson, P., & Edwards, J. (2016). Dual-purpose wheat: Improving grazing management using a smartphone app (PSS 2170). Oklahoma State University & Kansas State University.

Long, N. V., Assefa, Y., Schwalbert, R., & Ciampitti, I. A. (2017). Maize yield and planting date relationship: A synthesis-analysis for US high-yielding contest-winner and field research data. *Frontiers in Plant Science, 8*, Article 2106. https://doi.org/10.3389/fpls.2017.02106

Ma, J., Shang, C., Zhang, X., Yin, B., & Zhen, W. (2025). Optimized Agronomic Management in North China Plain to Maintain Wheat (*Triticum aestivum* L.) Yield While Reducing Water and Fertilizer Inputs. *Agronomy*, *15*(5), 1053. https://doi.org/10.3390/agronomy15051053

Ma, S.-C., Wang, T.-C., Guan, X.-K., & Zhang, X. (2018). Effect of sowing time and seeding rate on yield components and water use efficiency of winter wheat by regulating the growth redundancy and physiological traits of root and shoot. *Field Crops Research, 221*, 166–174. https://doi.org/10.1016/j.fcr.2018.02.028

Maulana, F., D. Anderson, J., J. Butler, T., & Ma, X.-F. (2020). Improving Dual-Purpose Winter Wheat in the Southern Great Plains of the United States. In Recent Advances in Grain Crops Research. IntechOpen. https://doi.org/10.5772/intechopen.86417

McCormick, J. I., Paulet, J. W., Bell, L. W., Seymour, M., Ryan, M. P., & McGrath, S. R. (2021). Dual-purpose crops: The potential to increase cattle liveweight gains in winter across southern Australia. Animal Production Science, 61(11), 1189–1201. https://doi.org/10.1071/AN19231

McPherson, R. A., et al., 2007: "Statewide monitoring of the mesoscale environment: A technical update on the Oklahoma Mesonet" J. Atmos. Oceanic Technol. 24, 301–321.

Mhawej, M., Gao, X., Reilly, J. M., & Abunnasr, Y. (2024). Corn, soybeans and winter wheat water requirements over the contiguous United States between 2013 and 2021: The application of the SEBALIGEE v2 global model. *Journal of Hydrology, 630*, Article 130782. https://doi.org/10.1016/j.jhydrol.2024.130782

Miner, G. L., Delgado, J. A., Ippolito, J. A., Johnson, J. J., Kluth, D. L., & Stewart, C. E. (2022). Wheat grain micronutrients and relationships with yield and protein in the U.S. Central Great Plains. *Field Crops Research, 279*, Article 108453. https://doi.org/10.1016/j.fcr.2022.108453

Mitchell-MCCallister, D., Cano, A., & West, C. (2020). Meta-analysis of crop water use efficiency by irrigation system in the Texas High Plains. *Irrigation Science, 38*, 535–546. https://doi.org/10.1007/s00271-020-00696-x

Moghbel, F., Fazel, F., Aguilar, J., Mosaedi, A., & Lollato, R. P. (2024). Long-term investigation of the irrigation intervals and supplementary irrigation strategies effects on winter wheat in the U.S. Central High Plains based on a combination of crop modeling and field studies. *Agricultural Water Management, 304*, Article 109077. https://doi.org/10.1016/j.agwat.2024.109077

Mourtzinis, S., Edreira, J. I. R., Grassini, P., Roth, A. C., Casteel, S. N., Ciampitti, I. A., Kandel, H. J., Kyveryga, P. M., Licht, M. A., Lindsey, L. E., & Mueller, D. S. (2018). Sifting and winnowing: Analysis of farmer field data for soybean in the US North-Central region. *Field Crops Research, 221*, 130–141. https://doi.org/10.1016/j.fcr.2018.02.022

Mourtzinis, S., Rattalino Edreira, J. I., Conley, S. P., & Grassini, P. (2017). From grid to field: Assessing quality of gridded weather data for agricultural applications. *European Journal of Agronomy, 82*(A), 163–172. https://doi.org/10.1016/j.eja.2016.10.013

Munaro, L. B., Hefley, T. J., DeWolf, E., Haley, S., Fritz, A. K., Zhang, G., Haag, L. A., Schlegel, A. J., Edwards, J. T., Marburger, D., Alderman, P., Jones-Diamond, S. M., Johnson, J., Lingenfelser, J. E., Uneda-Trevisoli, S. H., & Lollato, R. P. (2020). Exploring long-term variety performance trials to improve environment-specific genotype × management recommendations: A case study for winter wheat. *Field Crops Research, 255*, Article 107848. https://doi.org/10.1016/j.fcr.2020.107848

Nielsen, D. C., Unger, P. W., & Miller, P. R. (2005). Efficient water use in dryland cropping systems in the Great Plains. *Agronomy Journal, 97*, 364–372. https://doi.org/10.2134/agronj2005.0364

Nielsen, D.C., 2018. Dry bean water use/yield production function to estimate dryland yields in the US Central High Plains. *Field Crops Research*, *228*, pp.60-67.

Ochsner, T., Rocateli, A., Tomlinson, P., Edwards, J., Lollato, R. P., & Patrignani, A. (2017). Dual-purpose wheat: Improving grazing management using a smartphone app (PSS-2170). Oklahoma State University Extension. https://extension.okstate.edu/fact-sheets/dual-purpose-wheat-improving-grazing-management-using-a-smartphone-app.html

Onyekwelu, I., Zipper, S., Welch, S., & Sharda, V. (2025). Quantifying future climate impacts on maize productivity under different irrigation management strategies: A high-resolution spatial analysis in the U.S. Great Plains. *Agricultural Water Management, 313*, Article 109490. https://doi.org/10.1016/j.agwat.2025.109490

Parton, W. J., Gutmann, M. P., Merchant, E. R., Hartman, M. D., Adler, P. R., McNeal, F. M., & Lutz, S. M. (2015). Measuring and mitigating agricultural greenhouse gas production in the US Great Plains, 1870–2000. *Proceedings of the National Academy of Sciences of the United States of America, 112*(34), E4681–E4688. https://doi.org/10.1073/pnas.1416499112

Patrignani, A., Lollato, R. P., Ochsner, T. E., Godsey, C. B., & Edwards, J. T. (2014). Yield gap and production gap of rainfed winter wheat in the southern Great Plains. *Agronomy Journal, 106*, 1329–1339. https://doi.org/10.2134/agronj14.0011

Pedersen, S. M., Boesen, M. V., & Ørum, J. E. (2013). Institutional and structural barriers for implementing on-farm water saving irrigation systems. *Food Economics, 9*(sup5), 11–26. https://doi.org/10.1080/2164828X.2013.859576

Pfeiffer, L., & Lin, C. Y. C. (2014). The effects of energy prices on agricultural groundwater extraction from the High Plains Aquifer. *American Journal of Agricultural Economics, 96*, 1349–1362.

Post, L., Bergkvist, G., Carlsson, G., Delin, S., Ekholm, E., Parsons, D., & Hetta, M. (2019). Integrating dual-purpose with single-purpose crops for forage and grain production in Sweden. In Grassland Science in Europe (Vol. 31, pp. 637–639).

Prudic, D. E. (1989). *Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model* (Open-File Report 88–729). U.S. Geological Survey. https://doi.org/10.3133/ofr88729

Pumphrey, F. V. (1970). Semidwarf winter wheat response to early spring clipping and grazing. Agronomy Journal, 62(5), 641–643. https://doi.org/10.2134/agronj1970.00021962006200050028x

Redmon, L. A., Krenzer, E. G., Jr., Bernardo, D. J., & Horn, G. W. (1996). Effect of wheat morphological stage at grazing termination on economic return. Agronomy Journal, 88(1), 94–97. https://doi.org/10.2134/agronj1996.00021962008800010020x

Reuter, R. R., & Horn, G. W. (2002). Cool season perennial grasses as complementary forages to winter wheat pasture. The Professional Animal Scientist, 18(1), 44–51. https://doi.org/10.15232/S1080-7446(15)31483-2

Ritchie, J. T., & Basso, B. (2008). Water use efficiency is not constant when crop water supply is adequate or fixed: The role of agronomic management. *European Journal of Agronomy, 28*(3), 273–281. https://doi.org/10.1016/j.eja.2007.08.003

Ritchie, J. T., & Otter, S. (1985). Description and performance of CERES-Wheat: A user-oriented wheat yield model. In *ARS wheat yield project* (ARS-38, pp. 159–175). National Technical Information Service.

Rodell, M., & Famiglietti, J. S. (2002). The potential for satellite-based monitoring of groundwater storage changes using GRACE: The High Plains aquifer, central US. *Journal of Hydrology, 263*(1–4), 245–256. https://doi.org/10.1016/S0022-1694(02)00060-4

Romero Soler, J., Grassini, P., Broyaka, A., PileCCo, I., Giordano, N., Andersen Onofre, K., Draper, M. A., Wagner, V., Talakhadze, G., Dzirkvadze, D., Shanoyan, A., Thiele, S., Blodgett, P., Odeh, O. O., & Lollato, R. (2026). *Narrowing yield gaps in Armenia and Georgia wheat-based systems for food security in times of war* [Preprint]. SSRN. https://doi.org/10.2139/ssrn.6641586

Ruiz Diaz, D. (2024). Soil test interpretations and fertilizer recommendations in Kansas (MF2586). Kansas State University Agricultural Experiment Station and Cooperative Extension Service. https://bookstore.ksre.ksu.edu/pubs/soil-test-interpretations-and-fertilizer-recommendations_MF2586.pdf

Sadras, V. O., & Angus, J. F. (2006). Benchmarking water-use efficiency of rainfed wheat in dry environments. *Australian Journal of Agricultural Research, 57*, 847–856. https://doi.org/10.1071/AR05359

Sadras, V. O., & Lawson, C. (2013). Nitrogen and water-use efficiency of Australian wheat varieties released between 1958 and 2007. *European Journal of Agronomy, 46*, 34–41. https://doi.org/10.1016/j.eja.2012.11.009

Saxton, K. E., & Rawls, W. J. (2006). Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society of America Journal, 70*, 1569–1578. https://doi.org/10.2136/sssaj2005.0117

Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L., & McMahon, P. B. (2012). Groundwater depletion and sustainability of irrigation in the U.S. High Plains and Central Valley. Proceedings of the National Academy of Sciences, 109(24), 9320–9325. https://doi.org/10.1073/pnas.1200311109

Schlegel, A. J., Assefa, Y., Haag, L. A., Thompson, C. R., & Stone, L. R. (2019). Soil water and water use in long-term dryland crop rotations. *Agronomy Journal, 111*, 2590–2599. https://doi.org/10.2134/agronj2018.09.0623

Schmall, E. (2025, June 19). “Amber waves of grain” recede in America’s heartland as wheat farmers struggle. *Reuters*. https://WWw.reuters.com/world/us/amber-waves-grain-recede-americas-heartland-wheat-farmers-struggle-2025-06-19/

Seymour, M., England, J. H., Malik, R., Rogers, D., Sutherland, A., & Randell, A. (2015). Effect of timing and height of defoliation on the grain yield of barley, wheat, oats and canola in Western Australia. Crop & Pasture Science, 66(4), 287–300. https://doi.org/10.1071/CP13411

Shroyer, J. P., Mikesell, M. E., & Lambert, D. M. (1996). *Kansas crop planting guide (L-818).* Kansas State University Agricultural Experiment Station and Cooperative Extension Service.

Simão, L. M., Peterson, D., Roozeboom, K. L., Rice, C. W., Du, J., Lin, X., & Lollato, R. P. (2023). Crop rotation and tillage impact yield performance of soybean, sorghum, and wheat. *Agronomy Journal, 115*, 658–673. https://doi.org/10.1002/agj2.21237

Simão, L.M., Cruppe, G., Michaud, J.P., Schillinger, W.F., Diaz, D.R., Dille, A.J., Rice, C.W. and Lollato, R.P., 2024. Beyond grain: Agronomic, ecological, and economic benefits of diversifying crop rotations with wheat. Advances in agronomy, 186, pp.51-112.

Slafer, G. A., Savin, R., & Sadras, V. O. (2023). Wheat yield is not causally related to the duration of the growing season. European Journal of Agronomy, 148, 126885. https://doi.org/10.1016/j.eja.2023.126885

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. (n.d.). *Soil Survey Geographic (SSURGO) Database for Kansas* [Data set]. Retrieved June 1, 2026.

Sprague, S. J., Kirkegaard, J. A., Graham, J. M., Dove, H., & Kelman, W. M. (2014). Crop and livestock production for dual-purpose winter canola (Brassica napus) in the high-rainfall zone of south-eastern Australia. Field Crops Research, 156, 30–39. https://doi.org/10.1016/j.fcr.2013.10.013

Stewart, Z. P., Paparozzi, E. T., Wortmann, C. S., Jha, P. K., & Shapiro, C. A. (2021). Effect of foliar micronutrients (B, Mn, Fe, Zn) on maize grain yield, micronutrient recovery, uptake, and partitioning. *Plants, 10*(3), Article 528. https://doi.org/10.3390/plants10030528

Suganya, A., Saravanan, A., & Manivannan, N. (2020). Role of zinc nutrition for increasing zinc availability, uptake, yield, and quality of maize (*Zea mays* L.) grains: An overview. *Communications in Soil Science and Plant Analysis, 51*(15), 2001–2021. https://doi.org/10.1080/00103624.2020.1820030

Taylor, K. W., Epplin, F. M., Brorsen, B. W., Fieser, B. G., & Horn, G. W. (2010). Optimal grazing termination date for dual-purpose winter wheat production. Journal of

Agricultural and Applied Economics, 42(1), 87–103. https://doi.org/10.22004/ag.econ.57148

Thornton, M. M., Shrestha, R., Wei, Y., Thornton, P. E., & Kao, S.-C. (2022). *Daymet: Daily surface weather data on a 1-km grid for North America, Version 4 R1* (Version 4.1) [Data set]. Oak Ridge National Laboratory Distributed Active Archive Center. https://doi.org/10.3334/ORNLDAAC/2129

Thornton, P. E., Shrestha, R., Thornton, M., Kao, S.-C., Wei, Y., & Wilson, B. E. (2021). Gridded daily weather data for North America with comprehensive uncertainty quantification. *Scientific Data, 8*, Article 190. https://doi.org/10.1038/s41597-021-00935-0

Tian LH, Bell LW, Shen YY, Whish JPM. (2012) Dual-purpose use of winter wheat in western China: cutting time and nitrogen application effects on phenology, forage production, and grain yield. Crop & Pasture Science 63, 520–528. https://doi.org/10.1071/CP12101

Trout, T. J., & DeJonge, K. C. (2018). Crop water use and crop coefficients of maize in the Great Plains. *Journal of Irrigation and Drainage Engineering, 144*(6), 04018009. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001309

U.S. Department of Agriculture, Farm Service Agency. (2025, August 1). *2025 acreage data as of August 1, 2025* [Data set]. https://WWw.fsa.usda.gov/tools/informational/freedom-information-act-foia/electronic-reading-room/frequently-requested/crop-acreage-data

U.S. Department of Agriculture, National Agricultural Statistics Service. (2024). *Cropland Data Layer (CDL)* [Data set]. Crop-CROScape. https://croplandcros.scinet.usda.gov/

U.S. Department of Agriculture, National Agricultural Statistics Service, Kansas Field Office. (2025, December). *Kansas wheat history*. https://WWw.nass.usda.gov/Statistics_by_State/Kansas/Publications/Cooperative_Projects/KS-wheat-history-25.pdf

U.S. Department of Agriculture, National Agricultural Statistics Service. (2026). *2025 state agriculture overview: Kansas*. USDA NASS. Retrieved July 22, 2026, from https://WWw.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=KANSAS

Unger, P. W., Stewart, B. A., Parr, J. F., & Singh, R. P. (1991). Crop residue management and tillage methods for conserving soil and water in semi-arid regions. *Soil and Tillage Research, 20*(2–4), 219–240. https://doi.org/10.1016/0167-1987(91)90041-U

United Nations, Department of Economic and Social Affairs, Population Division. (2024). World population prospects 2024: Summary of results (UN DESA/POP/ 2024/TR/No. 9). https://population.un.org/wpp/assets/Files/WPP2024_Summary- of-Results.pdf

United States Department of Agriculture, Farm Service Agency. (2025). Crop acreage data—2025 crop year [Data files]. https://www.fsa.usda.gov/tools/informational/ freedom-information-act-foia/electronic-reading-room/frequently-requested/ crop-acreage-data

United States Department of Agriculture, National Agricultural Statistics Service. (2022). Cattle production: Cattle sales up; inventory and number of farms with cattle down since 2017 (Highlights ACH22-20). USDA.

Van Bussel, L. G. J., Grassini, P., Van Wart, J., Wolf, J., Claessens, L., Yang, H., Boogaard, H., de Groot, H., Saito, K., Cassman, K. G., & Van Ittersum, M. K. (2015). From field to atlas: Upscaling of location-specific yield gap estimates. *Field Crops Research, 177*, 98–108.

Van Wart, J., Grassini, P., Yang, H., Claessens, L., Jarvis, A., & Cassman, K. G. (2015). Creating long-term weather data from thin air for crop simulation modeling. *Agricultural and Forest Meteorology, 209–210*, 49–58. https://doi.org/10.1016/j.agrformet.2015.02.020

Van Wart, J., Van Bussel, L. G. J., Wolf, J., Licker, R., Grassini, P., Nelson, A., Boogaard, H. L., Gerber, J., Mueller, N. D., Claessens, L. F. G., Van Ittersum, M. K., & Cassman, K. G. (2013). Use of agro-climatic zones to upscale simulated crop yield potential. *Field Crops Research, 143*, 44–55.

Vashisht, B. B., Maharjan, B., & Jalota, S. K. (2019). Management practice to optimize wheat yield and water use in changing climate. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science, 69*(7), 613–629. https://doi.org/10.1080/03650340.2019.1578957

Virgona, J. M., Gummer, F. A. J., & Angus, J. F. (2006). Effects of grazing on wheat growth, yield, development, water use, and nitrogen use. Australian Journal of Agricultural Research, 57(12), 1307–1319. https://doi.org/10.1071/AR06085

West, M. H., Smith, W. B., Mullenix, M. K., Rabinowitz, A. N., & Dillard, S. L. (2024). Evaluation of dual purpose wheat varieties in the Southeast United States. Applied Animal Science, 40(4), 446–455.

Whittemore, D. O., Butler, J. J., Jr., & Wilson, B. B. (2023). *2023 status of the High Plains aquifer in Kansas* (Technical Series 25). Kansas Geological Survey.

Whittemore, D. O., Butler, J. J., Jr., & Wilson, B. B. (2023). *2023 status of the High Plains aquifer in Kansas* (Technical Series No. 25). Kansas Geological Survey. https://doi.org/10.17161/kgsts.v25_2023.24127

Widmar, A. (2013). *Evaluation of secondary and micronutrients for soybean and wheat production* [Master's thesis, Kansas State University].

Wilson, B., Bartley, J., Emmons, K., Bagley, J., Wason, J., & Stankiewicz, S. (2005). *Water Information Management and Analysis System, Version 5, for the web—User manual* (Open-File Report No. 2005-30). Kansas Geological Survey, University of Kansas. https://geohydro.kgs.ku.edu/geohydro/ofr/2005_30/wimas_ofr2005_30.pdf

Winter, S. R., & Thompson, E. K. (1987). Grazing duration effects on wheat growth and grain yield. Agronomy Journal, 79(1), 110–114. https://doi.org/10.2134/agronj1987.00021962007900010023x

Xiang, Z., Bailey, R. T., Nozari, S., Husain, Z., Kisekka, I., Sharda, V., & Gowda, P. (2020). DSSAT-MODFLOW: A new modeling framework for exploring groundwater conservation strategies in irrigated areas. *Agricultural Water Management, 232*, 106033. https://doi.org/10.1016/j.agwat.2020.106033

Yang, L., Cheng, L., Wang, P., Zhao, H., Zhao, J., Zang, H., Yang, Y., & Zeng, Z. (2025). Diversified rotation systems improve grain yield and water use efficiency of winter wheat under limited irrigation in the North China Plain. The Crop Journal, 13(4), 1271–1280. https://doi.org/10.1016/j.cj.2025.05.012

Ye, Y., Wang, G., Huang, Y., Zhu, Y., Meng, Q., Chen, X., Zhang, F., & Cui, Z. (2011). Understanding physiological processes associated with yield–trait relationships in modern wheat varieties. Field Crops Research, 124(3), 316–322. https://doi.org/10.1016/j.fcr.2011.06.023

Yield Potential and Yield Gap Atlas [YPYGA]. (2026). Retrieved June 1, 2026, from https://WWw.yieldgap.com

Yonts, C. D. (2006). *Dry bean water management*. University of Nebraska Panhandle Research and Extension Center.

Yu, L., Zhao, X., Gao, X., & Siddique, K. H. M. (2020). Improving/maintaining water-use efficiency and yield of wheat by deficit irrigation: A global meta-analysis. *Agricultural Water Management, 228*, 105906. https://doi.org/10.1016/j.agwat.2019.105906

Zadoks, J. C., Chang, T. T., & Konzak, C. F. (1974). A decimal code for the growth stages of cereals. Weed Research, 14(6), 415–421. https://doi.org/10.1111/j.1365-3180.1974.tb01084.x

Zhang, T., He, Y., DePauw, R., et al. (2022). Climate change may outpace current wheat breeding yield improvements in North America. Nature Communications, 13, 5591. https://doi.org/10.1038/s41467-022-33265-1

Zhang, X., & Huang, J. (2025). Effects of long-term conservation tillage on soil quality and crop productivity: A global meta-analysis. Agriculture, Ecosystems & Environment, 359, 109123. https://doi.org/10.1016/j.agee.2025.109123

Zhang, X., Li, Y., Chen, H., & Wang, J. (2024). Optimizing irrigation strategies to improve water productivity under variable climate conditions. Agricultural Water Management, 301, 109077. https://doi.org/10.1016/j.agwat.2024.109077

Zhang, Y., Li, X., Wang, Z., & Chen, J. (2025). Quantifying wheat yield responses to variable irrigation strategies under semi-arid conditions. Field Crops Research, 315, 109152. https://doi.org/10.1016/j.fcr.2025.109152

Zou, Y., Saddique, Q., Ali, A., Xu, J., Khan, M. I., Qing, M., Azmat, M., Cai, H., & Siddique, K. H. M. (2021). Deficit irrigation improves maize yield and water use efficiency in a semi-arid environment. *Agricultural Water Management, 243*, Article 106483. https://doi.org/10.1016/j.agwat.2020.106483

Appendix A - Chapter 2 Supplementary Material

Appendix Table A.1 Seeding rates, dates of sowing, forage harvests, simulated grazing, and grain harvest specifications for experiment 1, field trials conducted in Hutchinson, Kansas. Each table provides specifications for a given season of the experiment.

2015-16					
TRIAL	**Seeding Rate (kg/ha)**	**Sowing**	**Forage Harvest**	**Simulated Grazing Events**	**Grain Harvest**
DUAL PURPOSE	134.5	09/25/2015	—	12/17/2015 02/04/2016 02/23/2016	06/16/2016
HOLLOW STEM	134.5	09/25/2015	01/05/2016	—	—
GRAIN ONLY	67.3	10/07/2015	—	—	06/16/2016

2016-17					
TRIAL	**Seeding Rate (kg/ha)**	**Sowing**	**Forage Harvest**	**Simulated Grazing Events**	**Grain Harvest**
DUAL PURPOSE	134.5	09/23/2016	—	02/10/2017 02/28/2017 03/05/2017	06/16/2017
HOLLOW STEM	134.5	09/23/2016	12/14/2016	—	—
GRAIN ONLY	67.3	10/13/2016	—	—	06/16/2017

2017-18					
TRIAL	**Seeding Rate (kg/ha)**	**Sowing**	**Forage Harvest**	**Simulated Grazing Events**	**Grain Harvest**
DUAL PURPOSE	134.5	09/20/2017	—	03/05/2018	06/15/2018
HOLLOW STEM	134.5	09/20/2017	—	—	—
GRAIN ONLY	67.3	10/19/2017	—	—	06/16/2017

2019-20					
TRIAL	**Seeding Rate (kg/ha)**	**Sowing**	**Forage Harvest**	**Simulated Grazing Events**	**Grain Harvest**
DUAL PURPOSE	134.5	09/18/2019	—	03/02/2020 03/11/2020 03/18/2020 03/26/2020	06/30/2020
HOLLOW STEM	134.5	09/18/2019	12/20/2019	—	—
GRAIN ONLY	67.3	10/10/2019	—	—	06/30/2020

2020-21					
TRIAL	**Seeding Rate (kg/ha)**	**Sowing**	**Forage Harvest**	**Simulated Grazing Events**	**Grain Harvest**
DUAL PURPOSE	134.5	09/17/2020	—	02/25/2021 03/01/2021 03/05/2021 03/12/2021 03/25/2021 03/30/2021	06/22/2021
HOLLOW STEM	134.5	09/17/2020	12/20/2020	—	—
GRAIN ONLY	84.1	10/08/2020	—	—	06/22/2021

2021-22					
TRIAL	**Seeding Rate (kg/ha)**	**Sowing**	**Forage Harvest**	**Simulated Grazing Events**	**Grain Harvest**
DUAL PURPOSE	134.5	09/21/2021	—	03/09/2022 03/15/2022 03/21/2022 03/24/2022 03/28/2022	06/16/2022
HOLLOW STEM	134.5	09/21/2021	12/20/2021	—	—
GRAIN ONLY	84.1	10/08/2021	—	—	06/16/2022

2022-23					
TRIAL	**Seeding Rate (kg/ha)**	**Sowing**	**Forage Harvest**	**Simulated Grazing Events**	**Grain Harvest**
DUAL PURPOSE	134.5	09/22/2022	—	03/06/2023 03/13/2023 03/20/2023 03/27/2023	07/01/2023
HOLLOW STEM	134.5	09/22/2022	12/16/2022	—	—
GRAIN ONLY	84.1	10/19/2022	—	—	07/01/2023

2023-24					
TRIAL	**Seeding Rate (kg/ha)**	**Sowing**	**Forage Harvest**	**Simulated Grazing Events**	**Grain Harvest**
DUAL PURPOSE	134.5	09/25/2023	—	02/26/2024 03/04/2024 03/11/2024 03/18/2024 03/25/2024	06/12/2024
HOLLOW STEM	134.5	09/25/2023	11/30/2023	—	—
GRAIN ONLY	84.1	10/17/2023	—	—	06/12/2024

2024-25					
TRIAL	**Seeding Rate (kg/ha)**	**Sowing**	**Forage Harvest**	**Simulated Grazing Events**	**Grain Harvest**
DUAL PURPOSE	134.5	09/20/2024	—	02/17/2025 02/24/2025 03/03/2025 03/10/2025 03/17/2025 03/24/2025 03/31/2025	06/28/2025
HOLLOW STEM	134.5	09/20/2024	12/12/2024	—	—
GRAIN ONLY	84.1	11/15/2024	—	—	06/28/2025

YEAR	**O.M**	**PH**	**PH**	**PH**	**NO3-N**	**NO3-N**	**NO3-N**	**NO3-N**	**P**	**K**	**CA**	**MG**	**NA**	**SO4-S**	**CL**	**CEC**
UNIT	ppm				ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	meq/100g
DEPTH (CM)	0–15	0-15	15–61	15–46	0-61	0–15	15–61	15–46	0–15	0–15	0–15	0–15	0–15	0–15	0–15	0–15
2016	2.2	4.88	6.34			10.3	5.6		74.7	238	1379	231	17.9	7.9	9	15
2017	1.94	7.86	7			12.71	4.49		63.3	201.3	2172	180.6	12.8	7.8	4.8	12.9
2018	2.3	5.47	5.92		2.8	1.7			53.7	225.4	1339.2	240.4	5.8	5.3	6.9	19.3
2019	2.3	7.2	7.8			21.3	20.5		50.8	205	3516	164	13	5.8	7	19.53
2020	1.88	5.97	7.2			60.36	33.57		55.7	234.8	1997.3	163.8	13.2	18.3	6.1	18.2
2021	3	7.3	7.7			71.5	28.3		29	366.3	4713.3	101.2	12.1	4.2		25.4
2022	2.5	5.4		7		47		43.5	61.2	324.5	1952.6	231.6	21.4	8.7	4.9	22.23
2023		8	8.2			9.8	15.7			182	6018	93	8	3.5	5.8	31.4
2024	2.1	6.6	7		1.7	1.9			34	510				3.1	4.6	23
2025	**2.3**	6.9	7.9			21	20		39	221	2871	194		9		17

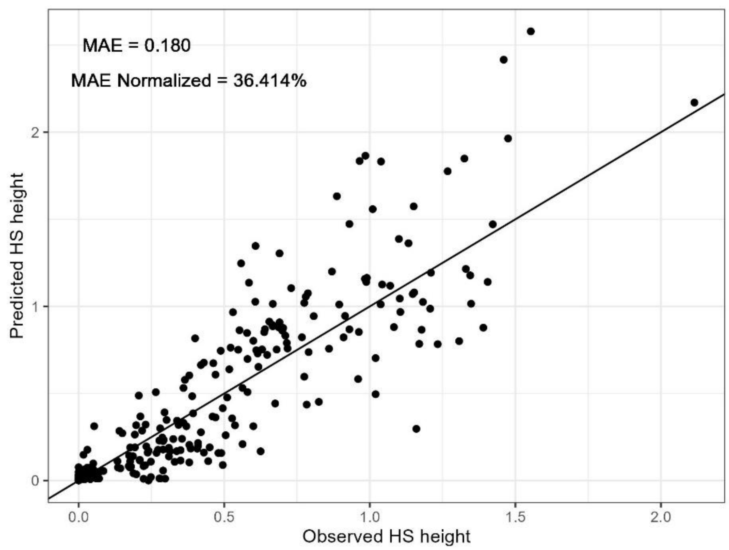
Appendix Table A.2 Soil fertility measured at experimental field sites in Hutchinson, Kansas (experiment 1) from 2015-2025.

Appendix Table A.3 Seeding rates, dates of sowing, forage harvests, simulated grazing, and grain harvest specifications for experiment 1, field trials conducted in El Reno, Oklahoma. Each table provides specifications for a given season of the experiment.

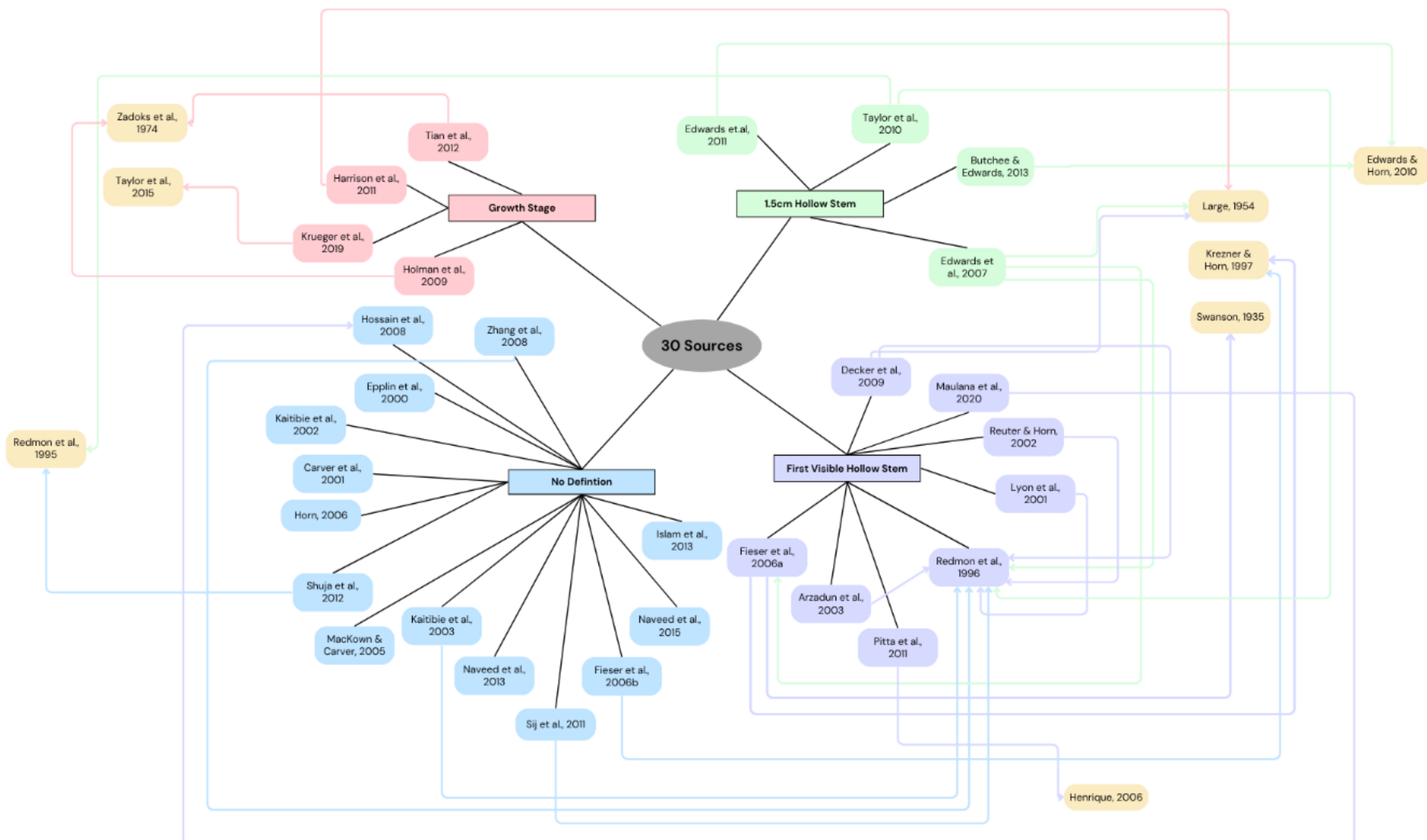
2021-22			
TRIAL	**Seeding Rate (kg/ha)**	**Sowing**	**Grain Harvest**
DUAL PURPOSE	134.5	10/06/2021	06/16/2022
GRAIN ONLY	67.3	10/26/2021	06/16/2022
Dual purpose grazed 12/06/2021– 02/28/2022 at 347.5 kg body weight per ha			

2022-23			
TRIAL	**Seeding Rate (kg/ha)**	**Sowing**	**Grain Harvest**
DUAL PURPOSE	134.5	10/19/2022	06/20/2023
GRAIN ONLY	67.3	11/21/2022	06/20/2023
Dual purpose grazed 01/08/2023–03/01/2023 at 230.9 kg body weight per ha			

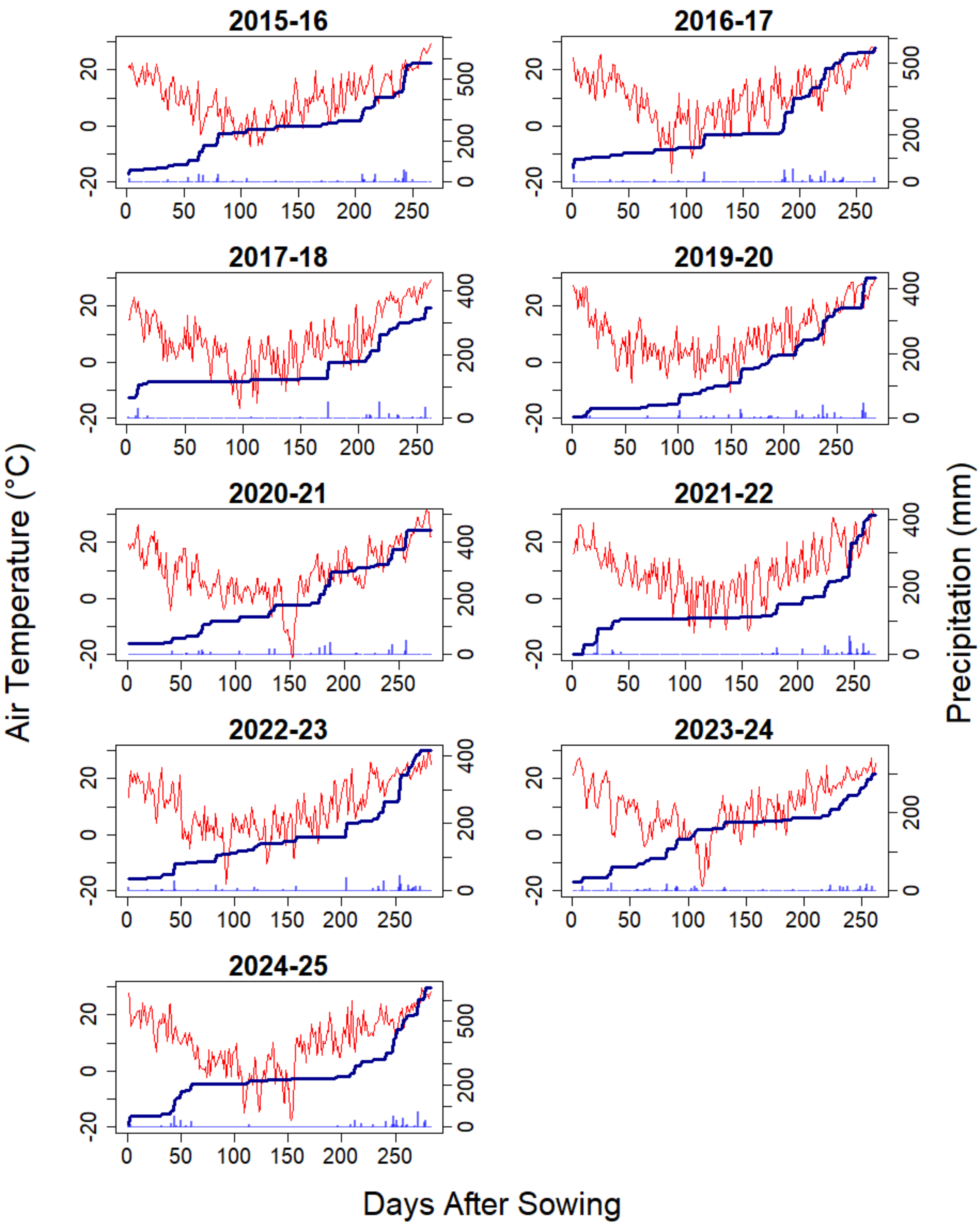
2023-24			
TRIAL	**Seeding Rate (kg/ha)**	**Sowing**	**Grain Harvest**
DUAL PURPOSE	134.5	09/25/2023	06/08/2024
GRAIN ONLY	67.3	10/17/2023	06/08/2024
Dual purpose grazed 11/29/2023–02/23/2024 at 345.2 kg body weight per ha			



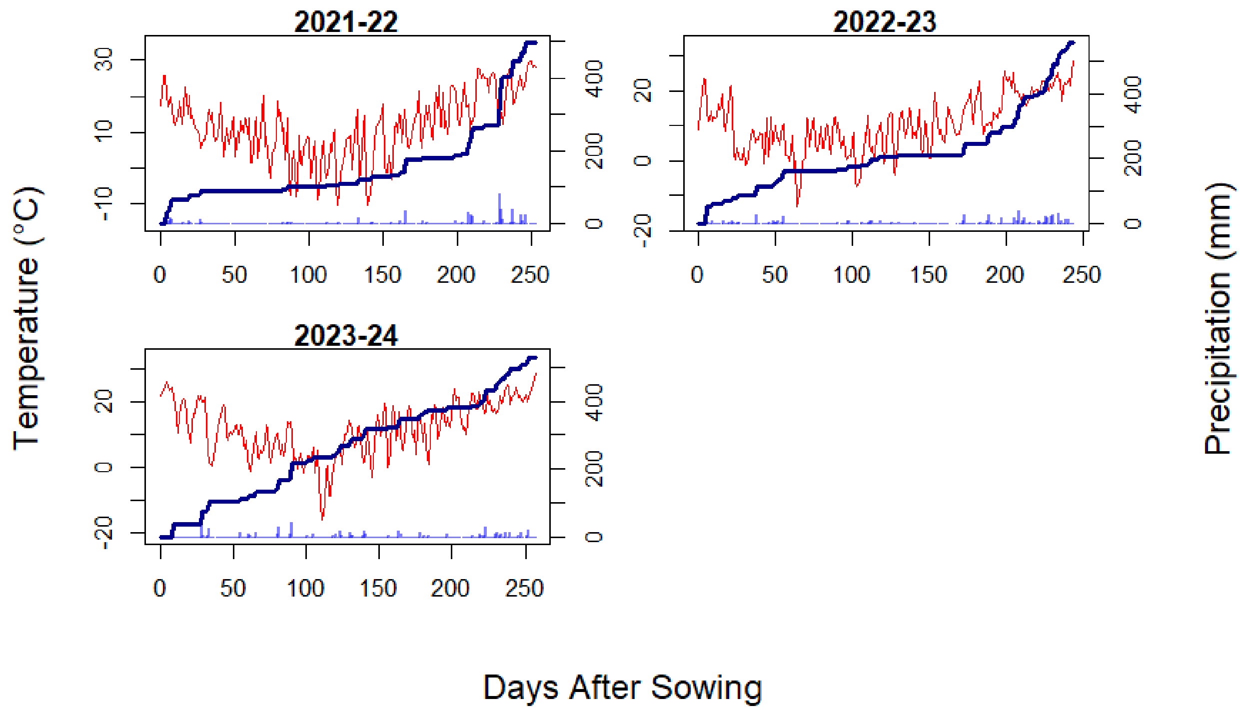
Appendix Figure A.1 Prediction ability of year-variety specific exponential models for hollow stem (HS) growth over time.



Appendix Figure A.2 Visualization of literature review. Sources are classified according to the provided definition of first hollow stem. Arrows depict major citations for the definition of first hollow stem from each source, pointing in the direction of the cited source.



Appendix Figure A.3 Environmental conditions experiment 1; Hutchison, Kansas. Days after sowing correspond to dual-purpose planting dates. Weather data comes from 'Hutch10SW' Kansas Mesonet station located at 37.931°, -98.02° (Kansas Mesonet, 2024). Red line is daily temperature, blue line is cumulative precipitation, and blue bars are daily precipitation over the course of the growing season.



Appendix Figure A.4 Environmental conditions experiment 2; El Reno, Oklahoma. Days after sowing correspond to dual-purpose planting dates. Data from El Reno (ELRE) Oklahoma Mesonet station located at 35.548480°, -98.036540° (McPherson et al., 2007; Brick et al., 1995). Red line is daily temperature, blue line is cumulative precipitation, and blue bars are daily precipitation over the course of the growing season.

Appendix Table A.4 Sources included in literature review

Arzadun, M. J., Arroquy, J. I., Laborde, H. E., & Brevedan, R. E. (2003). Grazing pressure on beef and grain production of dual-purpose wheat in Argentina. *Agronomy Journal, 95*(5), 1157–1164. https://doi.org/10.2134/agronj2003.1157

Butchee, J. D., & Edwards, J. T. (2013). Dual-purpose wheat grain yield as affected by growth habit and simulated grazing intensity. *Crop Science, 53*(5), 1686–1692. https://doi.org/10.2135/cropsci2013.01.0033

Carver, B. F., Khalil, I., Krenzer, E. G., Jr., & MacKown, C. T. (2001). Breeding winter wheat for a dual-purpose management system. *Euphytica, 119*(3), 231–234.

Decker, J. E., Epplin, F. M., Morley, D. L., & Peeper, T. F. (2009). Economics of five wheat production systems with no-till and conventional tillage. *Agronomy Journal, 101*(2), 364–372. https://doi.org/10.2134/agronj2008.0159

Edwards, J. T., Carver, B. F., & Payton, M. E. (2007). Relationship of first hollow stem and heading in winter wheat. *Crop Science, 47*(5), 2074–2077.

Edwards, J. T., Carver, B. F., Horn, G. W., & Payton, M. E. (2011). Impact of dual-purpose management on wheat grain yield. *Crop Science, 51*(5), 2181–2185. https://doi.org/10.2135/cropsci2011.01.0043

Epplin, F. M., Hossain, I., & Krenzer, E. G., Jr. (2003). Winter wheat fall–winter forage yield and grain yield response to planting date in a dual-purpose system. *Agronomy Journal, 95*(5), 1179–1188. https://doi.org/10.2134/agronj2003.1179

Fieser, B. G., Horn, G. W., Edwards, J. T., & Krenzer, E. G., Jr. (2006a). Timing of grazing termination in dual-purpose winter wheat enterprises. *The Professional Animal Scientist, 22*(2), 210–216.

Fieser, B. G., Horn, G. W., Edwards, J. T., & Krenzer, E. G., Jr. (2006b). Timing of grazing termination in dual-purpose winter wheat enterprises. *The Professional Animal Scientist, 22*, 210–216.

Harrison, M. T., Evans, J. R., Dove, H., & Moore, A. D. (2011). Dual-purpose cereals: Can the relative influences of management and environment on crop recovery and grain yield be dissected? *Crop and Pasture Science, 62*(11), 930–946. https://doi.org/10.1071/CP11066

Holman, J. D., Thompson, C. R., Hale, R. L., & Schlegel, A. J. (2009). Grazing effects on yield and quality of hard red and hard white winter wheat. *Agronomy Journal, 101*, 775–788. https://doi.org/10.2134/agronj2008.0163x

Horn, G. W. (2006). Growing cattle on winter wheat pasture: Management and herd health considerations. *Veterinary Clinics of North America: Food Animal Practice, 22*(2), 335–356.

Hossain, I., Epplin, F. M., & Krenzer, E. G., Jr. (2003). Planting date influence on dual-purpose winter wheat forage yield, grain yield, and test weight. *Agronomy Journal, 95*(5), 1179–1188. https://doi.org/10.2134/agronj2003.1179

Islam, M., Obour, A., Saha, M., Nachtman, J., Cecil, W., & Baumgartner, R. (2013). Grain yield, forage yield, and nutritive value of dual-purpose small grains in the Central High Plains of the USA. *Crop Management, 12.* https://doi.org/10.1094/CM-2012-0154-RS

Kaitibie, S., Epplin, F. M., Brorsen, B. W., Horn, G. W., Krenzer, E. G., Jr., & Paisley, S. I. (2003). Optimal stocking density for dual-purpose winter wheat production. *Journal of Agricultural and Applied Economics, 35*(1), 29–38.

Kaitibie, S., Epplin, F. M., Krenzer, E. G., Jr., & Zhang, H. (2002). Economics of lime and phosphorus application for dual-purpose winter wheat production in low-pH soils. *Agronomy Journal.*

Krueger, E. S., Ochsner, T. E., & Quiring, S. M. (2019). Development and evaluation of soil moisture-based indices for agricultural drought monitoring. *Agronomy Journal, 111*(3), 1–15. https://doi.org/10.2134/agronj2018.09.0558

Lollato, R. P., Marburger, D., Holman, J. D., Tomlinson, P., Presley, D., & Edwards, J. T. (2017). *Dual-purpose wheat: Management for forage and grain production (MF3375).* Kansas State University Agricultural Experiment Station and Cooperative Extension Service.

Lyon, D. J., Baltensperger, D. D., & Siles, M. (2001). Wheat grain and forage yields are affected by planting and harvest dates in the Central Great Plains. *Crop Science, 41*(3), 488–492.

MacKown, C. T., & Carver, B. F. (2005). Fall forage biomass and nitrogen composition of winter wheat populations selected from grain-only and dual-purpose environments. *Crop Science, 45*(1), 322–328.

Maulana, F., Anderson, J., Butler, T., & Ma, X.-F. (2019). Improving dual-purpose winter wheat in the Southern Great Plains of the United States. https://doi.org/10.5772/intechopen.86417

Naveed, K., Khan, M. A., Baloch, M. S., Khan, N., & Nadim, M. A. (2013). Effect of time of nitrogen application on morphological and physiological attributes of dual-purpose wheat. *Pakistan Journal of Botany, 45*(4), 1299–1305.

Pitta, C. S. R., Soares, A. B., Assmann, T. S., Adami, P. F., Sartor, L. R., Migliorini, F., Sollenberger, L. E., & Assmann, A. L. (2012). Dual-purpose wheat grain and animal production under different grazing periods. *Pesquisa Agropecuaria Brasileira, 46*(10), 1385–13

Redmon, L. A., Krenzer, E. G., Jr., Bernardo, D. J., & Horn, G. W. (1996). Effect of wheat morphological stage at grazing termination on economic return. *Agronomy Journal, 88*(1), 94–97.

Reuter, R. R., & Horn, G. W. (2002). Cool season perennial grasses as complementary forages to winter wheat pasture. *The Professional Animal Scientist, 18*(1), 44–51. https://doi.org/10.15232/S1080-7446(15)31483-2

Shuja, M., Ali, M., Iqbal, A., & Khalil, I. (2010). Evaluating the response of wheat genotypes to forage clipping. *International Journal of Agriculture and Biology, 12.*

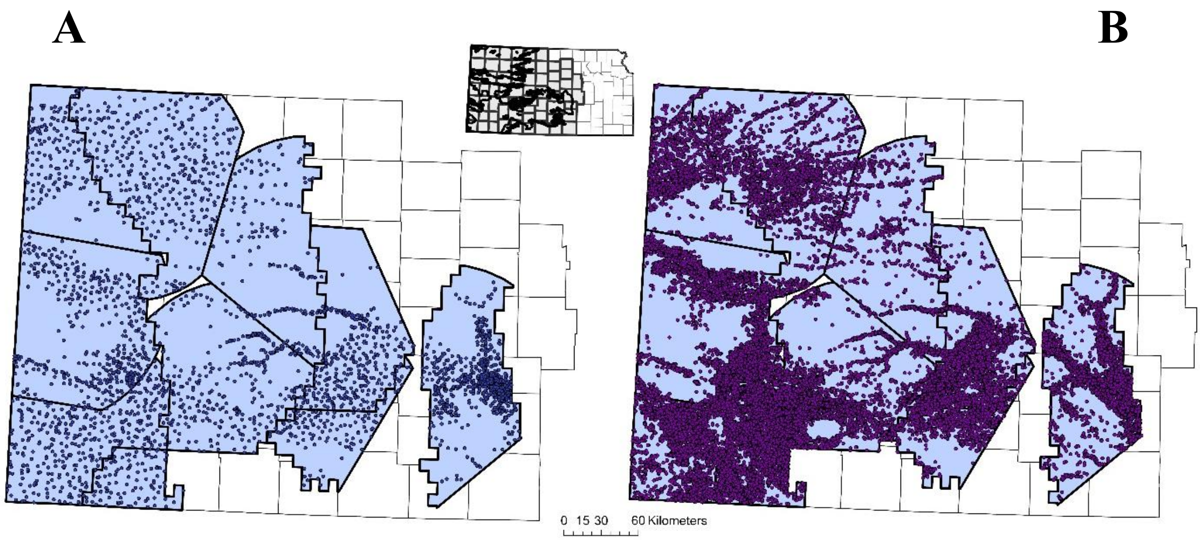
Sij, J., Belew, M., & Pinchak, W. (2016). Nitrogen management in no-till and conventional-till dual-use wheat/stocker systems. *Texas Journal of Agriculture and Natural Resources, 24*, 38–49. https://txjanr.agintexas.org/index.php/txjanr/article/view/48

Taylor, K. W., Epplin, F. M., Brorsen, B. W., Fieser, B. G., & Horn, G. W. (2010). Optimal grazing termination date for dual-purpose winter wheat production. *Journal of Agricultural and Applied Economics, 42*(1), 87–103. https://doi.org/10.22004/ag.econ.57148

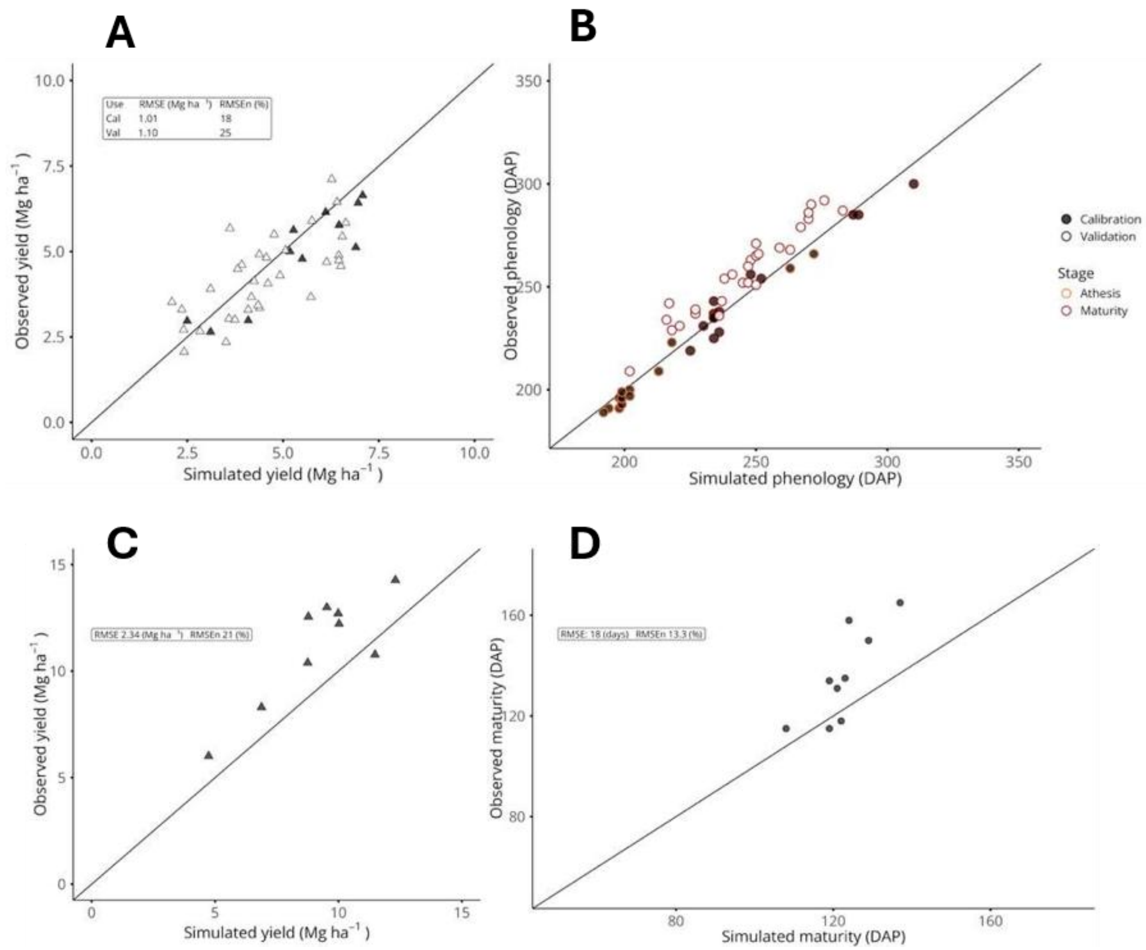
Tian, L. H., Bell, L. W., Shen, Y. Y., & Whish, J. P. M. (2012). Dual-purpose use of winter wheat in western China: Cutting time and nitrogen application effects on phenology, forage production, and grain yield. *Crop and Pasture Science, 63*(6), 520–528. https://doi.org/10.1071/CP12101

Zhang, X.-C., Phillips, W. A., Garbrecht, J. D., Steiner, J. L., & Hunt, L. A. (2008). A wheat grazing model for simulating grain and beef production: Part I—Model development. *Agronomy Journal, 100*(5), 1242–1247.

Appendix B - Chapter 3 Supplementary Material



Appendix Figure B.1 (A) Data locations for well-specific annual water use reports contributing at least one value from 2000 to 2025 to the computation of Q-stable. (B) Data locations for water-level changes contributing at least one value from 2000 to 2025 to the computation of Q-stable.



Appendix Figure B.2 (A) Calibration and validation of simulated yields for CERES wheat model. (B) Calibration and validation of simulated phenology for CERES wheat model. (C) Validation of simulated yields for CERES maize model. (D) Validation of simulated maturity date for CERES maize model.

Appendix Table B.1 38 site-years of wheat field data used for validation of the CERES wheat model utilized in analysis.

Location	Lat	Long	Wheat class	Use	Planting	Harvest	Yield
					------------Date------------		Mg ha^{-1}
Conway	37.46	-97.625	Hard red winter	Validation	10/11/16	6/22/17	4.688
Ellsworth	38.725	-97.444	Hard red winter	Validation	10/7/16	6/27/17	6.447
McPherson	38.364	-97.7	Hard red winter	Validation	10/7/15	6/28/16	4.571
McPherson	38.364	-97.7	Hard red winter	Validation	10/11/16	6/20/17	4.882
Ashland Bottoms	39.126	-96.637	Hard red winter	Validation	10/14/20	6/23/21	4.819
Ashland Bottoms	39.126	-96.637	Hard red winter	Validation	10/12/21	6/29/22	3.301
Belleville	39.814	-97.675	Hard red winter	Validation	10/5/20	7/1/21	4.298
Great Bend	37.931	-98.02	Hard red winter	Validation	10/20/21	6/20/22	2.711
Hays	38.849	-99.345	Hard red winter	Validation	9/28/21	6/23/22	3.902
Hutchinson	37.931	-98.02	Hard red winter	Validation	10/8/20	6/16/21	4.061
Hutchinson	37.931	-98.02	Hard red winter	Validation	10/21/21	6/14/22	2.066
Leoti	38.483	-101.328	Hard red winter	Validation	9/25/20	7/12/21	5.676
Leoti	38.483	-101.328	Hard red winter	Validation	9/25/21	7/5/22	3.519
Manhattan	39.209	-96.592	Hard red winter	Validation	10/7/20	7/5/21	3.349
Manhattan	39.209	-96.592	Hard red winter	Validation	10/18/21	7/1/22	3.034
Colby	39.392	-101.069	Hard red winter	Validation	10/1/20	7/14/21	4.131
Larned	37.936	-99.253	Hard red winter	Validation	9/30/15	6/22/16	7.114
McGregor	31.485	-97.316	Hard red winter	Validation	10/21/22	NA	3.667
Bushland	35.187	-102.08	Hard red winter	Validation	10/30/18	NA	4.609
Akron	40.155	-103.142	Hard red winter	Validation	9/26/23	7/14/24	5.899
Bushland	35.187	-102.08	Hard red winter	Validation	10/15/19	NA	2.666
Chillicothe	33.757	-99.862	Hard red winter	Validation	11/7/23	NA	3.667
Lamar	38.094	-102.631	Hard red winter	Validation	9/8/23	6/21/24	3.007
Chillicothe	33.757	-99.862	Hard red winter	Validation	11/10/22	NA	2.348
Walsh	37.382	-102.299	Hard red winter	Validation	9/19/23	6/24/24	3.432
Altus	34.587	-99.338	Hard red winter	Validation	11/3/22	5/31/23	3.297
Chickasha	35.032	-97.914	Hard red winter	Validation	10/25/21	6/16/22	4.742
Chickasha	35.032	-97.914	Hard red winter	Validation	10/21/22	6/7/23	5.436
Chickasha	35.032	-97.914	Hard red winter	Validation	10/16/23	6/14/24	5.841
Lahoma	36.384	-98.111	Hard red winter	Validation	10/20/21	6/14/22	5.494
Lahoma	36.384	-98.111	Hard red winter	Validation	10/27/22	6/15/23	4.916
Lahoma	36.384	-98.111	Hard red winter	Validation	10/11/23	6/6/24	5.032
Muenster	33.651	-97.197	Hard red winter	Validation	11/8/23	NA	4.488
Brookings	44.325	-96.769	Hard red winter	Validation	9/19/23	6/21/24	5.563

Havre	48.498	-109.801	Hard red winter	Validation	9/25/19	7/21/20	3.441
MountVernon	43.687	-98.672	Hard red winter	Validation	10/4/23	7/15/24	5.442
Havre	48.498	-109.801	Hard red winter	Validation	9/17/20	7/6/21	3.291
Platte	43.484	-99.048	Hard red winter	Validation	10/4/23	7/15/24	5.771

Appendix Table B.2 9 site-years of field data used to select the representative CERES Maize model used in analysis.

Location	Lat	Long	Planting	Harvest	Yield
			------------Date------------		Mg ha^{-1}
Belleville	39.814	-97.675	05/17/24	10/22/24	8.30
Belleville	39.814	-97.675	05/18/22	10/31/22	10.77
Good Well	38.364	-97.7	04/29/21	08/22/21	12.99
Good Well	38.364	-97.7	04/26/22	08/19/22	6.01
Good Well	38.364	-97.7	04/28/10	08/24/10	12.55
Manhattan	39.209	-96.592	04/24/24	09/06/24	14.27
Manhattan	39.209	-96.592	05/16/22	09/24/22	12.21
Ottawa	38.538	-95.241	04/24/24	09/21/24	12.70
Ottawa	38.538	-95.241	04/29/22	09/10/22	10.39

Appendix Table B.3 Classification of dominant soil classification simulated for each geographic buffer. DUL is drained upper limit and LL is lower limit.

Buffer	Soil Reference Number	Taxonomic order	DUL	LL	Depth
			cm/cm^3		cm
Elkhart	1	Mollisols	0.31	0.11	149
Goodland	1	Mollisols	0.31	0.11	149
	2	Entisols	0.31	0.11	185
	3	Alfisols	0.31	0.11	189
Colby	1	Entisols	0.31	0.11	177
	2	Mollisols	0.31	0.11	165
Tribune	1	Mollisols	0.31	0.11	149
	2	Vertisols	0.31	0.11	185
	3	Alfisols	0.31	0.11	189
Dodge City	1	Mollisols	0.31	0.11	177
Greensburg	1	Alfisols	0.31	0.11	161

	2	Mollisols	0.354	0.207	160
Hays	1	Mollisols	0.31	0.11	175
	2	Entisols	0.31	0.11	177
Great Bend	1	Mollisols	0.31	0.11	166
Hutchinson	1	Entisols	0.31	0.11	159
	2	Mollisols	0.354	0.207	162

Appendix Table B.4 Coordinates used to collect weather data for each geographic buffer.

Reference Weather Station	**Latitude**	**Longitude**
Elkhart	37.0058	-101.887
Goodland	39.3672	-101.693
Colby	39.38	-101.07
Tribune	38.46625	-101.775
Dodge City	37.7686	-99.9678
Greensburg	37.6025	-99.3022
Hays	38.83	-99.35
Great Bend	38.3614	-98.8228
Hutchinson	37.931	-98.02

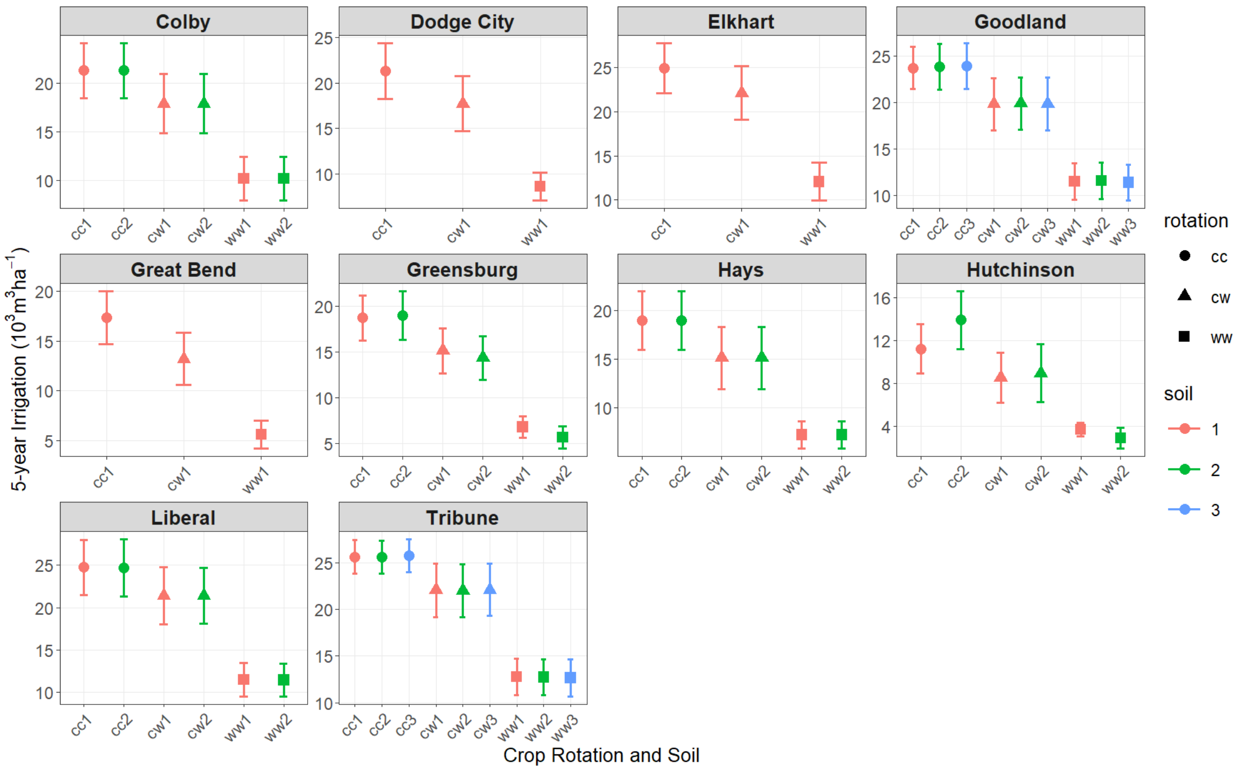
Appendix Table B.5 Planting dates used for each primary crop/cropping sequence in long-term cropping simulations.

Buffer	**Continuous corn**	**Continuous wheat**	**Wheat (following corn)**
Elkhart	May 3rd	October 2nd	October 7th
Goodland	May 5th	September 29th	October 3rd
Colby	May 5th	September 29th	October 3rd
Tribune	May 3rd	October 1st	October 5th
Dodge City	May 3rd	October 2nd	October 7th
Greensburg	April 20th	October 10th	October 15th
Hays	May 3rd	October 2nd	October 7th
Great Bend	May 3rd	October 2nd	October 7th
Hutchinson	April 20th	October 8th	October 12th

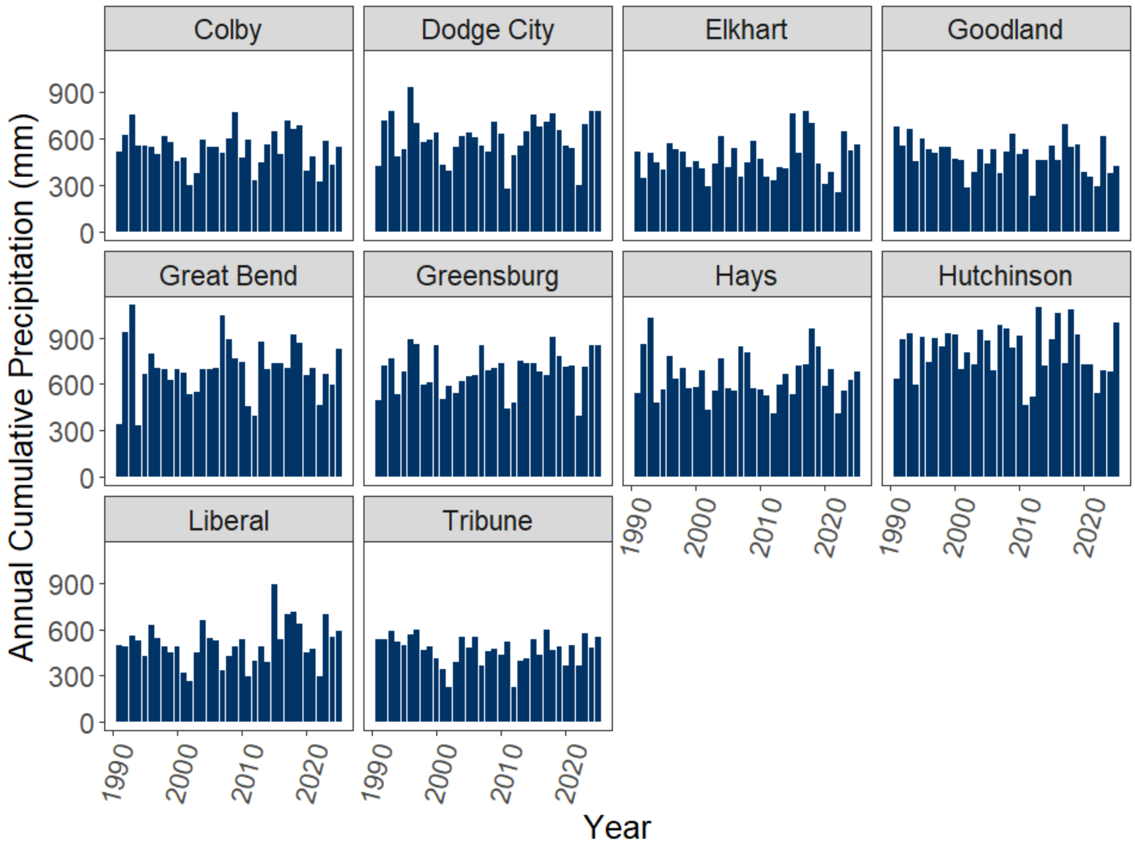
Appendix Table B.6 Description of variables collected in the farmer survey.

Section	**Variables**
Whole Farm Overview	Total farm size, typical crop rotation irrigated, typical crop rotation dryland, irrigated wheat area, years of experience irrigating wheat, water restrictions
Field Characteristics	Coordinate location, field size, purpose of crop, previous crop irrigation status, previous crop, previous crop purpose
Planting	Planting date, seeding rate, cultivar, seed source, seed treatment, profile water at planting, row spacing, seeding rate, tillage method
Inputs	Manure use, fungicide use, insecticide use, herbicide use, all fertilizer dates or application, amounts, and product names
Irrigation	Irrigation method, irrigation trigger factors, water source, system capacity, sprinkler nozzle spacing, all dates and quantities of irrigation application
Harvest	Harvest date, grain yield, major events impacting yield

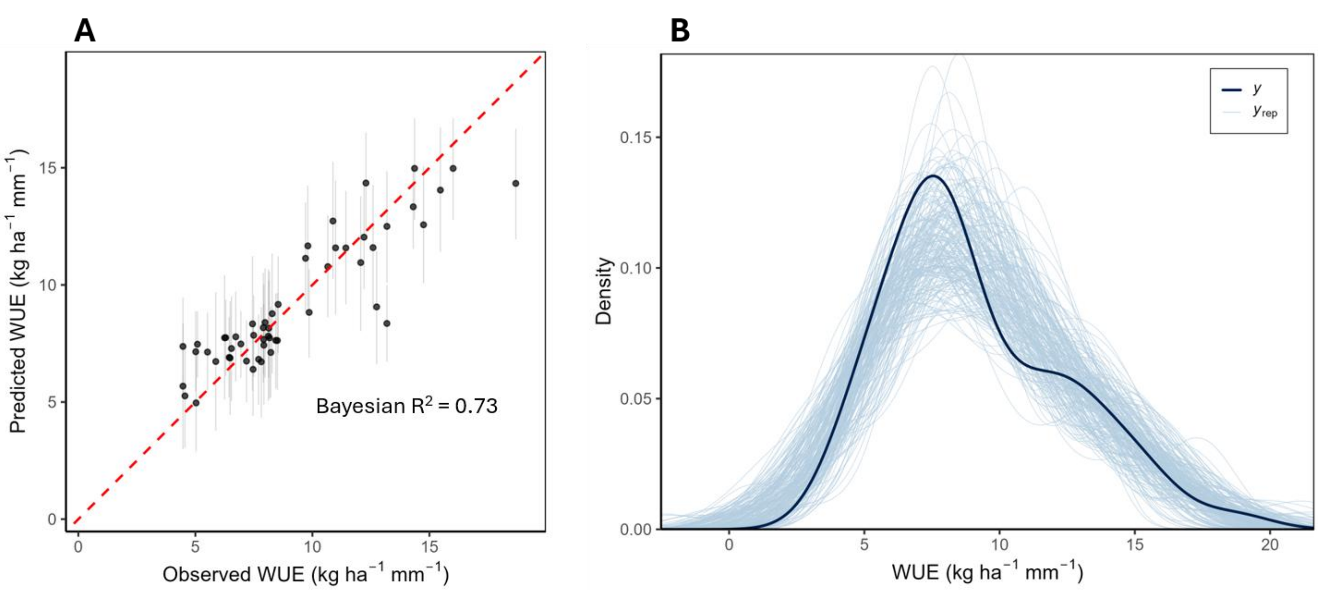
Appendix Figure B.3 Simulated maize and wheat yields for long-term simulations (1991-2025) in each of ten regions, under continuous maize, continuous wheat, and maize-wheat rotations.



Appendix Figure B.4 Irrigation applied in 5-year periods for 3 crop rotations; maize-corn (CW, triangle), continuous wheat (WW, square), and continuous maize (CC, circle) for each dominant soil type simulated by region. Soil reference numbers are found in Supplementary Table 1. Points are averages for simulations 1996-2025 with standard deviations depicted by error bars.

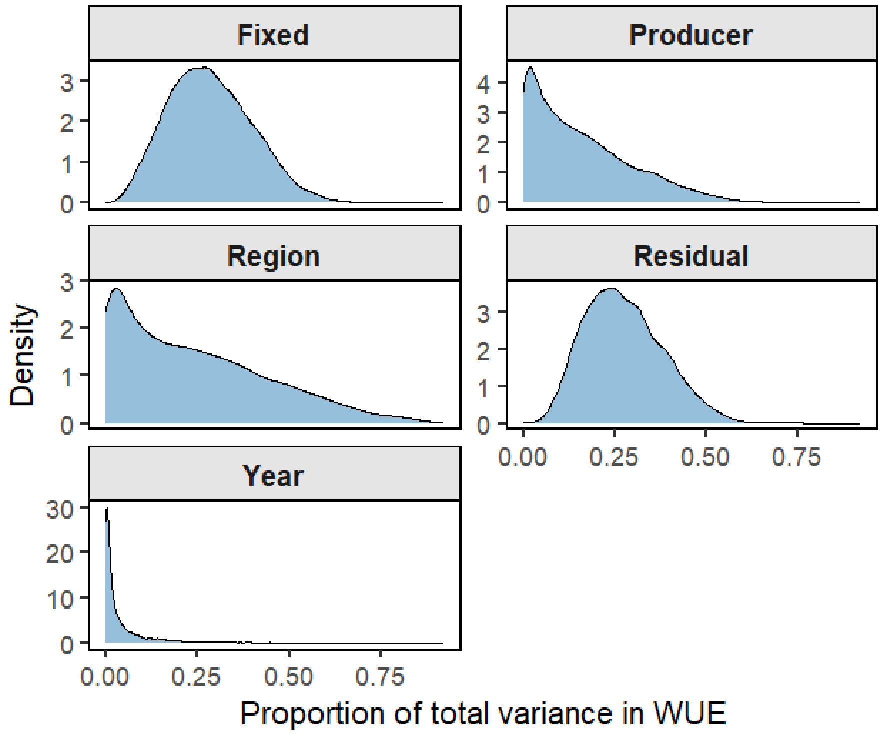


Appendix Figure B.5 Annual cumulative precipitation in simulation years 1991-2025 for each geographic region. Data from coordinate-based Daymet queries.



Appendix Figure B.0.6 Posterior predictive performance of the Bayesian model for water-use efficiency (WUE). (A) Observed versus predicted WUE, the red line indicates perfect agreement.

(B) Posterior predictive density comparing the distribution of observed (dark blue) to posterior draws (light blue)



Appendix Figure B.7 Posterior distributions of variance components for water-use efficiency (WUE) from the Bayesian hierarchical model. Each panel shows the posterior density of the proportion of total variance attributed to specific fixed and random effects.