

Winter wheat response to nitrogen rate and management across Kansas environments

by

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Abstract

Nitrogen (N) fertilizer management is one of the primary factors driving winter wheat (*Triticum aestivum* L.) productivity, profitability, and grain quality in Kansas; however, agroclimatic variability across the state represents a consistent challenge for optimizing fertilizer use. This research evaluated winter wheat response to N fertilization across ten site-years during the 2023-2024 and 2024-2025 growing seasons. The first study evaluated grain yield and grain protein concentration responses to increasing N rates (0 to 202 kg N ha⁻¹) to characterize environmental variability and determine site-specific agronomic optimum N rate (ANOR). The second study evaluated the effectiveness of diverse management strategies, varying in N source, timing, placement, and inhibitor use, applied at a constant N rate of 67 kg N ha⁻¹, using the site-specific expected responses from the first study as a baseline to compare management effects. Results from the first study indicated that grain yield response was highly variable, with AONR ranging from 116 to 185 kg N ha⁻¹ across responsive environments. Environments with limited seasonal precipitation or high initial residual soil N exhibited weak or no grain yield response, whereas grain protein concentration increased consistently across all site-years, often continuing to increase after grain yield had plateaued. In the second study, alternative management strategies did not consistently improve grain yield relative to the expected baseline; instead, environmental conditions were the primary determinants of grain yield at a constant N rate. However, nitrogen management more frequently influenced grain protein concentration and apparent recovery efficiency (ARE). Strategies that delayed or split N application, such as split-applied UAN, often increased grain protein, while fall or early spring applications tended to result in lower protein responses. These findings demonstrate that the effectiveness of both N rate and management practices is defined by site-year conditions, including precipitation patterns

and soil N supply. This research highlights the necessity of site-specific management, suggesting that producers must balance N rate and timing decisions based on local environmental grain yield potential and specific goals for grain yield versus grain quality.

Table of Contents

List of Figures	vii
List of Tables	viii
Acknowledgements	ix
Dedication	xi
Chapter 1 - General Introduction	1
References	5
Chapter 2 - Evaluating Winter Wheat Response to Nitrogen Fertilizer Across Kansas	
Environments	7
ABSTRACT	7
INTRODUCTION	9
MATERIALS AND METHODS	11
Sites and Experimental Design	11
Soil Characterization and Grain Measurements	12
Statistical Analysis	13
RESULTS AND DISCUSSION	16
Environmental Characterization	16
Grain Yield Response to N Fertilizer	17
Agronomic Optimum Nitrogen Rate Across Responsive Environments	18
Grain Protein Concentration Response to Nitrogen Rate	21
CONCLUSIONS	24
REFERENCES	26
TABLES AND FIGURES	29
Chapter 3 - Winter Wheat Response to Nitrogen Management Strategies Across Kansas	
Environments	36
ABSTRACT	36
INTRODUCTION	38
MATERIALS AND METHODS	40

Sites and Experimental Design	40
Soil and Plant Sampling and Analysis	42
Statistical Analysis.....	44
RESULTS AND DISCUSSIONS.....	46
Environmental Characterization	46
Nitrogen Management Effects on Grain Yield and Agronomic Efficiency.....	47
Grain Protein Response Relative to the Site-Specific Expected Response	50
Apparent Recovery Efficiency Relative to the Site Specific Expected Response	53
CONCLUSIONS	55
REFERENCES	57
TABLES AND FIGURES	61
Chapter 4 - General Conclusions	69

List of Figures

Figure 2.1. Initial soil inorganic nitrogen measured prior to planting.	31
Figure 2.2. Seasonal distribution of daily precipitation, maximum air temperature, and cumulative precipitation for each site-year in Kansas.	32
Figure 2.3. Quadratic grain yield response to nitrogen fertilizer rate and estimated agronomic optimum nitrogen rate (AONR) across six responsive site-years in Kansas.	33
Figure 2.4. Comparison of yield-maximizing and protein-maximizing nitrogen (N) rates across responsive winter wheat site-years.	34
Figure 2.5. Relative grain yield and grain protein concentration responses to nitrogen (N) fertilizer across winter wheat site-years.	34
Figure 2.6. Relative grain yield and grain protein response to nitrogen fertilizer rate at four representative yield-nonresponsive site-years in Kansas.	35
Figure 3.1. Initial soil inorganic nitrogen measured prior to planting.	63
Figure 3.2. Seasonal distribution of daily precipitation, maximum air temperature, and cumulative precipitation for each site-year in Kansas.	64
Figure 3.3. Estimated yield differences from the site-specific baseline for management treatments across yield-responsive site-years in Kansas.	65
Figure 3.4. Estimated differences in Agronomic Efficiency from the site-specific baseline for management treatments across yield-responsive site-years in Kansas.	66
Figure 3.5. Estimated difference in grain protein concentration from the site-specific baseline for management treatments across site-years in Kansas.	67
Figure 3.6. Estimated difference in Apparent Recovery Efficiency from the site-specific baseline for management treatments across Kansas site-years.	68

List of Tables

Table 2.1. Site-years information including crop management, and soil properties measured before planting for winter wheat experiments in Kansas.....	29
Table 2.2. Winter wheat grain yield response to nitrogen fertilizer rates across ten site-years in Kansas.	30
Table 2.3. Winter wheat grain protein concentration response to nitrogen fertilizer rates across ten site-years in Kansas.	31
Table 3.1. Site-years information including crop management, and soil properties measured before planting for winter wheat experiments in Kansas.....	61
Table 3.2. Nitrogen Management Treatment Evaluated Across Kansas Research Stations (2023-2025).	62

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Dedication

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Chapter 1 - General Introduction

Winter wheat (*Triticum aestivum* L.) is one of the most important crops in Kansas agriculture, contributing significantly to regional and national grain production. As one of the largest wheat-producing states in the United States, Kansas plays an important role in meeting domestic and global wheat demand (USDA-FAS, 2025). Achieving high wheat productivity depends on effective nutrient management, particularly nitrogen (N), which is a key nutrient driving crop growth, grain yield, and quality (Havlin et al., 2016). However, the efficiency of applied N fertilizer is often limited by environmental losses such as ammonia volatilization, nitrate leaching, and denitrification. These loss pathways reduce producers' economic return and contribute to environmental concerns (Havlin et al., 2016). As a result, improving nitrogen use efficiency (NUE) while maintaining grain yield and grain quality is a major challenge in modern wheat production systems (Fixen et al., 2014).

In Kansas, a primary challenge in optimizing N management is the pronounced agroclimatic variability. Wheat grain yield potential and nitrogen fertilizer efficiency are strongly influenced by a longitudinal precipitation gradient, where annual rainfall ranges from approximately 400 mm in the west to 1200 mm in the east (Jaenisch et al., 2021; Lollato et al., 2017, 2020). Under water-limited conditions, moisture availability often establishes the crop's yield ceiling, whereas higher rainfall environments can increase yield potential and subsequent N demand (Jaenisch et al., 2021). In addition to climatic factors, edaphic properties such as soil texture, organic matter, and pH influence the soil's capacity to supply N through mineralization, further contributing to the complexity of management decisions (Havlin et al., 2016). Consequently, crop responses to N fertilization are inconsistent; in some environments, yield increases with increasing N rates, while in others, additional N provides little or no yield benefit.

Furthermore, grain protein concentration often responds differently from yield, continuing to increase even after yield response has plateaued (Giordano et al., 2024). This separation is frequently attributed to the dilution effect, where grain yield increases more rapidly than N can be accumulated and partitioned to the grain (Fowler, 2003). Therefore, winter wheat responses to N fertilization cannot be fully captured by yield alone.

While grain yield is typically the primary criterion for evaluating N response, it does not always reflect changes in grain quality or fertilizer efficiency. Grain protein concentration is an important component of winter wheat performance because it strongly influences grain quality. However, simultaneous increases in yield and protein are not always achieved, as both variables often respond differently to N supply. In many cases, grain protein responds more consistently to fertilization than yield, particularly when environmental conditions limit the crop's ability to convert additional N into greater grain production (Dick et al., 2016; Mohammed et al., 2013). This makes protein a valuable indicator for producers because it directly influences the marketability and milling value of the grain (Latshaw et al., 2016). Therefore, grain protein concentration should be considered alongside grain yield when evaluating winter wheat response to N fertilization.

In addition to grain yield and grain protein concentration, N management should also be evaluated by how efficiently applied fertilizer contributes to crop production. Nitrogen use efficiency provides a broader framework for assessing performance management because it links crop productivity with the use and recovery of applied nutrients and also helps interpret potential nutrient losses to the environment (Fixen et al., 2014). Because a single metric does not represent NUE, different indicators are needed to capture distinct aspects of N performance. Indicators such as agronomic efficiency (AE) and apparent recovery efficiency (ARE) are particularly

useful for short-term evaluation of fertilizer management, as they help distinguish productivity gains from the proportion of applied N recovered by the crop (Dobermann, 2007; Fixen et al., 2014). These indicators are especially important in winter wheat systems, where management practices may influence not only grain production, but also the effectiveness with which applied N is taken up and retained within the crop-soil system.

Despite the importance of grain protein concentration and NUE, N fertilizer recommendations are still typically based on the yield goal concept, where a specific N coefficient is multiplied by the expected yield to estimate fertilizer requirements (Havlin et al., 2016). Although this approach provides a useful framework, its accuracy depends on stable seasonal yield potential, which is rarely achieved in the variable environments of Kansas. As a result, this approach often fails to account for year-to-year fluctuations in indigenous soil N supply and moisture availability, highlighting the importance of determining the agronomic optimum nitrogen rate (AONR). However, AONR reflects crop response under a specific set of environmental and management conditions, and its value can vary widely across site-years. Evaluating AONR across diverse environments is therefore necessary to improve site-specific understanding of winter wheat response to N fertilization.

Although determining the appropriate N rate is fundamental, crop response also depends on how fertilizer is managed within the season. Practices such as split applications and tools such as inhibitors have been developed to improve N synchronization and potentially alter the crop's response curve, but results remain inconsistent across environments (Ballagh et al., 2025; Habibullah et al., 2018; Mohammed et al., 2013). Research indicates that the effectiveness of these strategies is highly site-specific; for instance, nitrification inhibitors can significantly reduce losses in wet, poorly drained soils, whereas urease inhibitors often show limited impact in

dryland systems where nitrogen loss potential is lower (Mohammed et al., 2016a). Because the N rate required to maximize yield is highly dependent on both environmental conditions and the management system employed (Aula et al., 2021a; Cui et al., 2006), it remains difficult to determine whether a successful crop response is due to the total amount of N applied or the specific management strategy. This limitation highlights the need to evaluate both N rate responses and constant rate management strategies across contrasting environments to better understand how environmental conditions shape winter wheat yield, grain protein concentration, and nitrogen use efficiency.

To address these limitations, this thesis integrates two complementary approaches within a single field experiment to examine nitrogen management in Kansas winter wheat systems. Both components were derived from the same field experiments, where N rate and management treatments were integrated within a single randomized experimental design. The first study quantified grain yield and grain protein responses to increasing N fertilizer rates across diverse site-years to characterize variability in crop response and determine environment-specific agronomic optimum nitrogen rates. The second study evaluated the effectiveness of nitrogen management strategies applied at a constant N rate, using site-specific expected responses as a baseline to isolate management effects from N rate effects. Together, these approaches provide a basis for a better understanding of how environmental conditions influence both the magnitude of N response and the effectiveness of management practices. Therefore, the overall objective of this thesis was to evaluate winter wheat response to nitrogen fertilization across Kansas environments by integrating N rate responses and constant rate management strategies to determine how environmental variability influences grain yield, grain protein concentration, and nitrogen use efficiency.

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Chapter 2 - Winter Wheat Response to Nitrogen Fertilizer Rate Across Kansas Environments

ABSTRACT

Nitrogen (N) availability is one of the primary factors limiting winter wheat productivity. However, crop response to N can vary across environments and years due to differences in water availability and soil N supply. The objective of this study was to evaluate the response of winter wheat (*Triticum aestivum* L.) grain yield and grain protein concentration to increasing N fertilizer rates across ten site-years in Kansas during the 2023 to 2024 and 2024 to 2025 growing seasons, and to estimate the agronomic optimum nitrogen rate (AONR) from the fitted grain yield response for each site-year. Field experiments were conducted in a randomized complete block design with four replications, and six N rates (34, 67, 101, 135, 168 and 202 kg N ha⁻¹) applied as urea at Feekes 6, plus a non-fertilized control. Grain yield and grain protein concentration were analyzed within each site-year, and quadratic models were used to estimate AONR where grain yield responded significantly. Grain yield responded significantly to N rates at seven site-years, while grain protein concentration responded at all site-years. The AONR varied from 116 to 185 kg N ha⁻¹ across responsive environments. Site-years with lower initial soil inorganic N and adequate seasonal precipitation generally showed greater grain yield response, while environments with lower rainfall or relatively high initial residual soil N showed a lower or no grain yield response. In contrast, grain protein concentration often increased even when grain yield response decreased. Across responsive site-years, the N rate associated with maximum grain protein concentration exceeded the N rate associated with maximum grain yield. Relative grain yield response plateaued at approximately 143 kg N ha⁻¹, whereas grain protein concentration continued to increase throughout the evaluated N-rate range. These results show

that winter wheat response to N fertilization in Kansas is highly variable across environments and that N requirements differ depending on whether the management objective is grain yield maximization or grain protein optimization. Therefore, site-specific N rate decisions should account for soil N supply, seasonal water availability, and the intended production goal, particularly when balancing grain yield and grain protein concentration.

INTRODUCTION

Winter wheat (*Triticum aestivum* L.) is one of the most important cereal crops in Kansas, representing approximately 18% of total United States wheat production (USDA-FAS, 2025). Nitrogen is the most important macronutrient driving winter wheat productivity, involved in tiller formation, leaf development, photosynthetic activity, and grain filling, which together determine grain yield and protein concentration (Havlin et al., 2016).

Considering the relevance of N for wheat production and its mobile nature in both soil and plants, selecting the right N rate is necessary to achieve profitable production while minimizing excess N remaining in the system. In practice, this is challenging because crop N requirement and the amount of plant-available N supplied by the soil can vary across environments and years (Havlin et al., 2016).

Grain yield typically increases with N rate up to an optimum level, beyond which additional N results in diminishing returns (Giordano et al., 2024). However, because the N demand and soil N supply vary substantially among environments, the N rate associated with maximum yield is also highly variable (Cui et al., 2006; Liu et al., 2016; Tsvey et al., 2021).

In Kansas, wheat yield variability is mainly influenced by the pronounced longitudinal precipitation gradient, where annual rainfall ranges from about 400 mm in the west to 1200 mm in the east, and water availability often defines the crop's yield ceiling and N fertilization efficiency (Jaenisch et al., 2021; Lollato et al., 2017, 2020). In addition to total precipitation, the timing and distribution of rainfall events can influence soil water availability and crop N uptake throughout the growing season. Under water-limited conditions, grain yield may be more limited by soil moisture than N supply, whereas in environments with higher rainfall, higher yield potential can increase crop demand for N (Cossani & Sadras, 2018). In addition to this climatic

variability, edaphic factors like soil texture, organic matter, pH, and initial inorganic N contribute to the complexity of N management by influencing the soil's capacity to supply N through mineralization (Havlin et al., 2016).

This environmental variability complicates the development of generalized N fertilizer recommendations across Kansas wheat systems. Traditional N recommendation models are often based on the yield goal concept, in which a specific N coefficient is multiplied by expected yield to estimate fertilizer requirement (Havlin et al., 2016). Although this approach provides a useful framework, its accuracy depends on stable seasonal yield potential. In the variable climate of Kansas, uniform N coefficients may fail to account for the year-to-year fluctuations in the indigenous soil N supply and moisture availability. This highlights the importance of estimating the Agronomic Optimum Nitrogen Rate (AONR), which provides a practical measure of the N rate required to maximize yield under a given set of conditions. Evaluating AONR across diverse environments can therefore improve understanding of site-specific winter wheat response to N fertilization.

Although optimizing grain yield is a major objective of N fertilization, in crops like wheat, evaluating crop response based solely on yield may overlook important quality responses. Grain protein concentration is also an important component of winter wheat performance. Grain protein reflects N accumulation in the grain and is directly related to grain quality, making it particularly relevant to production systems that value productivity quality. However, simultaneous increases in grain yield and grain protein concentration are not always achieved, as they do not necessarily respond similarly to increased N supply. For winter wheat, grain protein has a more consistent response to N fertilization than grain yield, particularly when environmental conditions limit the crop's ability to convert additional N into greater grain

production (Ballagh et al., 2025; Dhillon et al., 2020). Therefore, evaluating both variables provides a more complete understanding of winter wheat response to N fertilizer across contrasting environments.

Despite the recognized influence of environmental variability on both yield and grain quality responses to N fertilization, there is still limited understanding of how grain yield, AONR and grain protein concentration respond to increasing applied N under contrasting precipitation and soil N conditions. Improving this understanding is important for developing more environment-specific N management strategies. The objective of this study was to evaluate how winter wheat grain yield, AONR, and grain protein concentration respond to increasing N application rates across varying Kansas environments.

MATERIALS AND METHODS

Sites and Experimental Design

The study was conducted across ten site-years during the 2023–2024 and 2024–2025 winter wheat growing seasons. The site-years represented diverse environmental conditions, including variability in precipitation patterns and soil properties. Experiments were established at university research stations under no-till, rainfed conditions. Agronomic practices, such as wheat cultivar selection, crop rotation, and pesticide applications, varied among stations according to local management practices (Table 2.1). Precipitation and air temperature data were obtained from the Kansas Mesonet weather station nearest to each experimental site. Seasonal precipitation was calculated as cumulative rainfall from sowing to the soft dough growth stage for each site-year. Long-term precipitation was expressed as the 30-year average cumulative precipitation for the corresponding sowing-to-soft-dough period at each location, based on historical records (Kansas Mesonet, 2026). Daily precipitation, cumulative precipitation, and

daily maximum air temperature were used to characterize environmental conditions throughout the growing season.

The experimental design at each site-year was a randomized complete block design with four replications, with plot sizes ranging from 2 to 3.5 m in width and 12 m in length. Wheat growth stages were identified according to the Feekes scale (Feekes, 1954). Nitrogen rate treatments consisted of six fertilizer N rates (34, 67, 101, 135, 168, and 202 kg N ha⁻¹), applied as urea (46-0-0) at Feekes 6 (jointing), in addition to a non-fertilized control.

Soil Characterization and Grain Measurements

Composite soil samples were collected by block prior to sowing and fertilizer application to determine routine fertility status. At the 0-15 cm depth, composite samples consisted of 10 to 12 cores per block, collected with a 1.9-cm-diameter probe. At the 0-60 cm depth, composite samples consisted of 4 to 5 cores per block. All samples were oven-dried at 40 °C to constant weight, ground, and passed through a 2-mm sieve prior to chemical analysis.

Collected soils were analyzed at the Kansas State University Agronomy Soil Testing Laboratory. Samples collected at 0-15 cm depth were used to determine: (1) soil pH, using a 1:1 soil-to-water method; (2) soil organic matter, via the Loss on Ignition; (3) plant available P, using the Mehlich-3 extraction; and (4) exchangeable K, Ca, Mg, and Na, using ammonium acetate extraction. Micronutrients, including Fe, Zn, Cu, and Mn, were extracted using the DTPA method, following procedures described by Brown (1998).

Soil samples collected at 0-60 cm depth were analyzed for inorganic N (nitrate-N and ammonium-N) using 1 M potassium chloride (KCl) extraction (Brown, 1998). Extractable sulfur was determined using a monocalcium phosphate extraction.

Soil series for each location were identified using the USDA Web Soil Survey (USDA-NRCS, 2006). Selected pre-plant soil chemical properties used to characterize the experimental environments are summarized in Table 2.1.

Grain yield was determined by harvesting the central portion of each plot using a small-plot combine, with two to three border rows excluded from each side of the plot to minimize border effects. Harvested area varied among site-years according to combine header width and ranged from 13 to 20 m². Harvested grain was weighed, and grain moisture content was determined for each plot using a GAC-2500-AGRI grain analysis computer (Dickey John, Auburn, IL, USA). Grain yield was standardized to a 13.5% moisture basis and expressed as Mg ha⁻¹.

Grain protein concentration was determined on a whole-grain basis using a DS3 near-infrared spectrometer (FOSS Analytical, Hillerød, Denmark), using the FOSS wheat calibration, the output was expressed as g kg⁻¹.

Statistical Analysis

The agronomic optimum N rate (AONR) was estimated by fitting a quadratic regression model to grain yield as a function of N rate:

$$Y = \beta_0 + \beta_1 N + \beta_2 N^2,$$

where Y represents grain yield and N represents the nitrogen application rate. The AONR was defined as the N rate at which the predicted grain yield was maximized and was calculated as:

$$AONR = -\frac{\beta_1}{2\beta_2}.$$

This estimation was performed individually for site-years where grain yield showed evidence of response to N rate based on the mixed-model analysis. For site-years where the

response pattern did not support a stable quadratic optimum, AONR estimates were interpreted cautiously.

Statistical analysis was performed using a linear mixed-effects model approach with the ‘lme4’ (Bates et al., 2015) and ‘lmerTest’ (Kuznetsova et al., 2017) packages in R (version 4.4.0; R Core Team, 2024). Nitrogen rate was analyzed independently within each site-year as a fixed effect, while replication was considered a random effect. The overall effect of N rate was evaluated using Type III analysis of variance (ANOVA), with the Kenward-Roger (Kenward & Roger, 1997) approximation used to estimate denominator degrees of freedom.

For grain yield and grain protein concentration, *post hoc* mean separation was conducted using the ‘emmeans’ (Lenth & Piaskowski, 2017) and ‘multcomp’ packages. Estimated marginal means were compared using a compact letter display, with *p*-values adjusted for multiple comparisons using the Sidak method to control the family-wise error rate at $\alpha = 0.10$.

For site-years where the overall analysis supported fitting a response curve, quadratic mixed-effects models including replication as a random effect were fitted to describe the grain yield response and estimate AONR.

For Site 3, additional exploratory diagnostics indicated spatial variation across plot position within replicate. Plot position within replicate was derived from plot identification numbers and evaluated as a covariate in mixed-effects models to determine whether yield varied systematically with field position. These models were used to assess whether the observed N-rate response was influenced by spatial heterogeneity. Adjusted means by N rate were estimated from mixed models including plot position as a fixed covariate and replication as a random effect. Quadratic models including plot position were used for exploratory evaluation of AONR, and

this estimate was interpreted cautiously because the quadratic term was not supported after spatial adjustment.

To facilitate comparison between grain yield and grain protein responses in environments where grain yield response was limited, relative responses were calculated as the mean value at each N rate divided by the mean value of the 0 N treatment within the same site-year.

To compare N requirements for grain yield and grain protein concentration across environments, the N rates associated with maximum grain yield and maximum grain protein concentration were estimated for the six site-years where AONR could be estimated. Grain yield-maximizing N rates were obtained using the same approach described for AONR estimation. Because grain protein concentration often continued increasing across the evaluated N-rate range, protein-maximizing N rates were identified from predictions generated from mixed-effects models fitted to grain protein response. The estimated yield-maximizing and protein-maximizing N rates were then compared across these site-years.

To evaluate overall grain yield and grain protein responses to N fertilization across all environments, relative grain yield and relative grain protein concentration were calculated at the plot level by dividing each observation by the mean of the non-fertilized treatment within the same site-year. Relative responses were analyzed using linear mixed-effects models with N rate as a fixed effect and replication nested within location as a random effect. Estimated marginal means were obtained for each N rate and used to characterize overall response patterns across environments. Quadratic-plateau models were subsequently fitted to the estimated marginal means using the ‘soiltestcorr’ package (Correndo et al., 2023) to describe relative grain yield and grain protein responses and to estimate response breakpoints. These breakpoints were interpreted

as the N rate beyond which additional fertilizer N did not produce a meaningful increase in the relative response variable.

RESULTS AND DISCUSSION

Environmental Characterization

The experimental sites represented a diverse range of agroclimatic conditions across Kansas, covering significant gradients in both precipitation and soil properties (Table 2.1; Figure 2.1; Figure 2.2). The 30-year mean growing-period precipitation ranged from 246 mm to 518 mm (Kansas Mesonet, 2026). During the experimental period, cumulative growing-season precipitation followed a similar pattern, with Site 4 receiving the least rainfall (293 mm) and Site 8 receiving the most (746 mm). This precipitation gradient provided important context for interpreting site-level differences in winter wheat performance, as yield and yield gaps in Kansas have been associated with water availability and climatic conditions (Jaenisch et al., 2021). Water availability may also influence nitrogen uptake and crop metabolic activity, thereby affecting the expression of fertilizer responses across environments (Zhao et al., 2024).

In addition to differences in total precipitation, the timing and distribution of rainfall events varied among site-years, while seasonal temperature patterns were generally similar across environments (Figure 2.2). Several site-years, such as Sites 2, 6, 7, and 10, experienced prolonged periods of limited rainfall both prior and following N application at Feekes 6, whereas others received substantial precipitation shortly after application, such as Site 8. These differences influenced soil water availability and therefore the synchronization between N supply and crop demand, contributing to variation in N availability and crop uptake across environments.

Pre-plant soil properties also varied across site-years and likely contributed to differences in crop response to N fertilization. Soil organic matter ranged from 23 g kg⁻¹ to 34 g kg⁻¹, while soil pH ranged from strongly acidic (5.1) to moderately alkaline (7.9).

Initial soil fertility also differed among environments. Total inorganic N (NO₃⁻-N + NH₄⁺-N) ranged from 5.8 mg kg⁻¹ to 16.5 mg kg⁻¹. Extractable sulfate concentrations were generally low, ranging from 2.1 mg kg⁻¹ to 24 mg kg⁻¹. Soil P and K also varied widely, with extractable P ranging from 12 mg kg⁻¹ to 72 mg kg⁻¹, and exchangeable K from 141 mg kg⁻¹ to 516 mg kg⁻¹.

Together, these site-years provided a strong environmental gradient for evaluating winter wheat response to N rate across Kansas environments.

Grain Yield Response to N Fertilizer

Grain yield response to N application varied among site-years, with exact p-values reported for each environment (Table 2.2). These responsive environments were generally characterized by lower initial soil inorganic N and adequate moisture during the growing season (Figure 2.2), suggesting that fertilizer N was more likely to limit yield under those conditions. In contrast Sites 2, 7, and 10 had p-values greater than 0.10, suggesting that environmental constraints reduced the probability of obtaining additional grain yield from fertilizer N.

At Site 10, the absence of yield response was likely associated with the combination of low seasonal precipitation and relatively high initial soil inorganic N. In addition to receiving the lowest cumulative precipitation among site-years, rainfall remained limited throughout much of the growing season (Figure 2.2), suggesting that water availability may have constrained crop response regardless of fertilizer N supply. Under these conditions, crop yield potential was likely restricted more by water availability than by nutrient deficiency, consistent with Jaenish et al.

(2021). In addition, Lollato and Edwards (2015) found that existing soil N supply may have been sufficient to satisfy crop demand within that reduced yield ceiling. A similar interpretation may apply to Site 7, where relatively high initial soil inorganic N, favorable precipitation, and moderate soil organic matter may have supported sufficient N supply through mineralization, thereby minimizing any observable yield response to fertilizer N.

Site 6 represents a less clearly defined response pattern. Although the overall effect of N rate had a p-value of 0.09, post hoc comparisons did not separate individual treatment means. This indicates that the site had a weak overall response, with no distinct increase at specific rates. Pre-plant inorganic N at this site was not particularly high, suggesting that limited responsiveness was not explained solely due to initial soil supply and may have been influenced by other environmental or management-related factors that are not evaluated in this study.

Among responsive environments (Table 2.2), the shape and magnitude of the response varied. Some sites had a strong yield increase at lower N rates that leveled off as rates increased, whereas others continued responding to increasing N rates. These differences likely reflected variation in site-year conditions influencing attainable yield, soil N supply, and the crop's ability to utilize additional fertilizer N. Consequently, the agronomic benefit of increasing N rate differed among environments, indicating that generalized N recommendation approaches based primarily on expected yield may not fully capture the variability in crop response across Kansas environments.

Agronomic Optimum Nitrogen Rate Across Responsive Environments

The AONR varied considerably among the six site-years where the grain yield response supports estimation, ranging from 116 to 185 kg N ha⁻¹ (Figure 2.3). Although the overall grain yield response to N rate had p-values below 0.10 at seven site-years (Table 2.2), Site 6 was

excluded from AONR estimation because post hoc comparisons did not separate N rate means, indicating that the response was too weak or inconsistent to support a reliable optimum. This broad range in AONR likely reflects variation in N supply, seasonal conditions, and site-specific yield potential.

Site 1 had the greatest predicted maximum yield in the study, reaching 4.9 Mg ha⁻¹ with an AONR of 150 kg N ha⁻¹. Because Site 3 is a nearby location in a different growing season, comparison between these site-years provides useful context for interpreting seasonal effects. However, additional diagnostics indicated that Site 3 was strongly affected by spatial variation across plot position. After accounting for spatial variation, Site 3 had a fertilizer response, but the yield response across N rates was irregular and did not support a stable quadratic optimum. Therefore, the AONR estimated for Site 3 should be interpreted cautiously. The lower yield observed at Site 3 likely reflects lower growing-season precipitation relative to Site 1, in addition to within site spatial heterogeneity. Cumulative growing-season precipitation was 299 mm at Site 3 compared to 504 mm at Site 1 (Figure 2.2), consistent with previous work showing that water availability is a major determinant of achievable wheat yield in the Southern Great Plains (Lollato and Edwards, 2015).

At Site 4, the AONR was the lowest observed among responsive environments (116 kg N ha⁻¹), and yield peaked at intermediate N rates. This suggests that soil N supply and site-specific yield potential may have reduced the need for additional fertilizer N beyond intermediate rates. Site 8 also had a relatively moderate AONR (135 kg N ha⁻¹). In this case, high seasonal precipitation combined with high soil organic matter and the potential for greater in-season N mineralization may have reduced the fertilizer N required to maximize yield, consistent with

previous findings that crop responses to N fertilization tend to decline when soil N availability is greater (Jaenisch et al., 2026; Ruisi et al., 2016).

In contrast to the high-yielding environment, Site 9 had an overall grain yield response to N fertilization (Table 2.2), but the response pattern was modest and did not support a strong quadratic relationship. Although the fitted quadratic model suggested an AONR near 185 kg N ha⁻¹, the quadratic term had a p-value greater than 0.05, indicating that this estimate should be interpreted cautiously. Instead, the data suggest that yield generally increased with N rate across the tested range, with the clearest improvement occurring only at the higher N rates. This pattern suggests that yield response at Site 9 was weaker and less clearly defined than at other responsive site-years, and that the optimum rate was not clearly defined within the range of N applied. Field observations at Site 9 noted the presence of leaf rust-like symptoms later in the growing season. However, disease incidence and severity were not quantified, so the potential contribution of disease pressure to the observed yield could not be determined.

At Site 5, the AONR was 153 kg N ha⁻¹, yet the predicted maximum yield remained relatively low at 2.49 Mg ha⁻¹. This combination of moderate to high N requirement and a low yield suggests that factors other than fertilizer rate limited crop performance. Strong soil acidity (pH 5.1) identified at this site likely contributed to this response. Soil acidity can lead to aluminum toxicity and reduced phosphorus availability, both of which can restrict root development and nutrient uptake thereby preventing the crop from achieving the higher yield potential observed at sites with more neutral pH (Havlin et al., 2016; Lollato et al., 2013, 2019).

These AONR results suggest that optimum N rate was not determined by yield level alone. Instead, AONR should be interpreted as a site-year specific estimate of the fertilizer N required to maximize yield under the conditions of that environment, reflecting the balance

among crop N demand, soil N supply, and site-year conditions that influenced the crop's ability to convert added N into grain yield. These results reinforce the need for environment-specific N management due to the difficulty of predicting optimum N requirements across Kansas environments using recommendation approaches based primarily on expected yield.

Grain Protein Concentration Response to Nitrogen Rate

In contrast with grain yield, grain protein concentration responded to N rate at all site-years, with $p < 0.001$ (Table 2.2). Across environments, protein concentration generally increased with increasing N supply; however, the magnitude and shape of the response varied among site-years. This consistent response indicates that grain protein concentration was more sensitive than grain yield to changes in N availability across the evaluated environments.

Across all grain yield-responsive site-years, the N rate associated with maximum grain protein concentration exceeded the N rate associated with maximum grain yield (Figure 2.4). Differences between protein-maximizing and yield-maximizing N rates ranged from 17 to 70 kg N ha⁻¹, indicating that N rates sufficient to maximize grain yield were often insufficient to maximize grain protein concentration. This separation between grain yield and protein responses suggests that additional N continued to contribute to grain N accumulation even after grain yield responses had diminished, consistent with previous reports showing continued increases in grain protein and grain N uptake at higher N rates after grain yield responses plateaued, particularly when environmental conditions constrained grain yield formation (Mohammed et al., 2013).

This relationship is further supported by the relative response analysis across all evaluated environments (Figure 2.5). Relative grain yield increased with N rate up to an estimated breakpoint of 143 kg N ha⁻¹, beyond which additional N did not result in further grain yield increases. In contrast, relative grain protein concentration continued to increase throughout

the evaluated N-rate range, and no protein breakpoint was identified within the maximum N rate evaluated (202 kg N ha⁻¹). Together, these results demonstrate that grain protein concentration generally required greater N availability than grain yield, supporting the observation that N requirements for quality optimization frequently exceeded those required for yield maximization.

While Figure 2.4 summarizes the differences between yield-maximizing and protein-maximizing N rates across responsive environments, Figure 2.5 shows the overall relative grain yield and grain protein responses across all evaluated environments. The separation between grain yield and grain protein responses was particularly evident in environments where grain yield showed little response to N fertilization (Figure 2.6). Across these site-years, relative grain yield generally did not differ from the control across N rates, indicating little or no yield benefit from additional fertilizer N. In contrast, relative grain protein concentration consistently exceeded that of the non-fertilized control across N rates, indicating that protein remained responsive even when grain yield was weakly responsive or unchanged. These site-years further illustrate that grain protein concentration can respond more strongly and more consistently to N fertilization than grain yield under certain environmental conditions. This pattern is consistent with Ballagh et al. (2025), who reported that grain protein concentration responded more consistently than grain yield to N management practices, particularly under variable environmental conditions.

At Site 10, low seasonal precipitation and prolonged periods of limited rainfall throughout the growing season (Figure 2.2), combined with relatively high initial inorganic soil N, likely reduced the probability of yield response, while added N still contributed to higher grain protein concentration. Site 7 had a similar separation between grain yield and protein responses, but in this case relatively high residual soil N and favorable seasonal precipitation

suggest that existing soil N supply may have already met much of the crop N demand for yield. Site 2 also had a limited grain yield response, even though grain protein increased with N rate. Site 6 was less clear because the overall yield response was weak and individual N rates did not differ, but grain protein still increased with N rate.

These four site-years (Figure 2.6) demonstrate that different environmental and soil conditions can limit grain yield response to fertilizer N, while grain protein concentration remains responsive to additional N. Although the factors limiting grain yield response differed among environments, they resulted in a similar separation between grain yield and grain protein responses. In winter wheat systems, achievable grain yield is strongly influenced by environmental conditions, particularly precipitation (Lollato & Edwards, 2015) and the photothermal quotient during the critical period (Porker et al., 2025). As a result, fertilizer N may have little effect on grain yield when water availability, residual soil N, disease, or other site-specific factors limit crop performance. Under these conditions, added N may contribute more clearly to grain protein concentration than to grain yield.

This divergence suggests that, under some environmental conditions, added N influenced grain protein concentration more clearly than grain yield. This response is consistent with the concept of critical N dilution in winter wheat, as described by Justes et al. (1994), in which plants may accumulate N above the critical concentration required for maximum biomass production without a corresponding increase in growth. Under these conditions, additional N may contribute more to grain N accumulation than to increased biomass or grain yield. Similar responses have been reported in winter wheat under environmentally limited conditions, where grain protein concentration remained responsive to N fertilization even when grain yield

potential was restricted by factors such as limited moisture or other site-specific stresses (Dick et al., 2016; Mohammed et al., 2013).

From an agronomic perspective, the different responses of grain yield and grain protein responses to N fertilization are important because the value of increasing N rate depends on the production goal. Where the main objective is grain yield maximization, additional N may provide limited benefit in environments where yield is restricted by water availability, residual soil N, disease, or other site-specific factors. However, where grain protein is also a management goal, higher N rates may still provide a measurable advantage even when grain yield response is small. Therefore, N rate decisions in winter wheat should be evaluated not only in terms of grain yield response, but also in terms of grain quality response.

CONCLUSIONS

Across ten Kansas site-years, winter wheat response to N fertilization varied considerably. This variation was associated with differences in seasonal precipitation, the distribution of rainfall events throughout the growing season, and initial inorganic soil N content. Agronomic optimum N rate ranged from 116 to 185 kg N ha⁻¹ across responsive site-years, indicating that a single, uniform N recommendation is unlikely to maximize productivity across the diverse agroclimatic conditions of Kansas.

Across site-years, differences in predicted maximum yield were not explained by N rate alone, indicating that environmental conditions strongly influenced productivity. While N fertilization increased grain yield in responsive environments, the magnitude of the response varied considerably among site-years. These results suggest that fertilizer N can help crops approach their maximum yield when N is limiting, but the maximum yield achievable is strongly influenced by site-year conditions, particularly water availability and the timing of precipitation.

Nitrogen requirements for grain protein concentration exceeded those required for grain yield maximization across all grain yield-responsive site-years. Relative grain yield plateaued at an estimated N rate of 143 kg N ha⁻¹, whereas grain protein concentration continued to increase throughout the evaluated N-rate range. These results indicate that N requirements for grain quality optimization are greater than those required for yield maximization and help explain why grain protein concentration remained responsive to N fertilization even in environments where grain yield response was limited. This distinction highlights the importance of defining fertilizer recommendations according to specific production goals, whether targeting maximum grain yield or improved grain protein concentration.

Overall, these findings indicate that winter wheat response to N rate cannot be adequately described by a single recommendation across Kansas environments. Instead, N rate decisions should account for the yield level achieved under each site-year condition, soil N supply, and the intended production goal to better balance productivity and grain quality.

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TABLES AND FIGURES

Table 2.1. Site-years information, including crop management, and soil properties measured before planting for winter wheat experiments in Kansas.

Sites-years	Growing season	County	Soil series ^a	Subgroup ^b	Texture class	Previous crop	Variety	Planting date	pH	OM
										g kg ⁻¹
1	2023-2024	Riley	Bismarckgrove	FL. Hapludolls	Silt loam	Soybean	KS Providence	10/16/2023	6.9	27
2	2023-2024	Republic	Crete	PU. Argiustolls	Silty clay loam	Soybean	KS Ahearn	11/07/2023	5.3	25
3	2024-2025	Riley	Bismarckgrove	FL. Hapludolls	Silt loam	Soybean	KS Mako	11/16/2024	6.5	25
4	2024-2025	Republic	Crete	PU. Argiustolls	Silty clay loam	Soybean	KS Mako	10/29/2024	5.8	27
5	2024-2025	Republic	Crete	PU. Argiustolls	Silty clay loam	Soybean	KS Mako	11/17/2024	5.1	27
6	2024-2025	Reno	Nalim	UD. Argiustolls	Clay loam	Soybean	KS Providence	10/25/2024	7.6	24
7	2024-2025	Reno	Darlow	V. Natrustalfs	Clay loam	Soybean	KS Providence	10/25/2024	5.2	26
8	2024-2025	Franklin	Woodson	AB. Argiaquolls	Silty clay loam	Soybean	KS Providence	10/24/2024	6	32
9	2024-2025	Shawnee	Bismarckgrove	FL. Hapludolls	Loam	Soybean	Doublestop CL Plus	10/24/2024	6.7	23
10	2024-2025	Ellis	Roxbury	CU. Haplustolls	Silty clay loam	Wheat	Joe	10/15/2024	7.9	34

Note. All soil samples were collected prior to planting at a depth of 0–15 cm for soil analyses.

OM, organic matter; AB, Abruptic; CU, Cumulic; FL, Fluventic; PU, Pachic Udertic; UD, Udic; V, Vertic.

^aSource: Web Soil Survey.

^bSource: USDA-NRCS Official Soil Series Descriptions

Table 2.2. Winter wheat grain yield response to nitrogen fertilizer rates across ten site-years in Kansas.

N rate	Site-year									
	1	2	3*	4	5	6	7	8	9	10
	----- Mg ha ⁻¹ -----									
0	3.16 a	3.84	1.46 a	2.18 a	1.53 a	3.81	4.26	3.16 a	1.80 a	2.96
34	4.14 b	3.74	2.33 ab	2.43 ab	1.91 ab	4.06	3.90	3.70 b	1.83 a	3.04
67	4.69 bcd	4.27	1.79 a	2.73 b	2.21 bc	4.21	4.16	3.90 b	2.07 ab	2.72
101	4.37 bc	3.94	1.83 a	2.61 b	2.27 bc	4.24	4.09	4.06 b	2.01 ab	2.88
135	4.99 d	4.23	3.52 b	2.56 b	3.09 c	3.88	3.35	3.92 b	2.06 ab	2.99
168	4.72 cd	4.03	2.70 ab	2.58 b	2.26 bc	4.11	3.84	3.90 b	2.21 b	2.90
202	4.81 cd	4.06	2.25 ab	2.45 ab	2.40 bc	4.06	3.95	3.95 b	2.08 ab	2.94
	----- Standard error -----									
	0.16	0.17	0.35	0.14	0.13	0.19	0.22	0.11	0.11	0.26
	----- p – value -----									
	<0.001	0.165	0.003	0.006	<0.001	0.090	0.132	<0.001	0.018	0.858

Note. Values represent estimated marginal means from linear mixed models with N-rate treatment as a fixed effect and replication as a random effect. Standard errors are those associated with the estimated marginal means for each site-year. Within each site-year, means sharing the same letter are not significantly different at $\alpha = 0.10$ according to Sidak-adjusted pairwise comparisons. P-values are from Type III tests with the Kenward-Roger method for denominator degrees of freedom. Bold p-values indicate site-years with a $p < 0.10$.

* Site 3 was subsequently re-evaluated using models that included plot position as a covariate because exploratory diagnostics indicated spatial heterogeneity within the experimental area.

Table 2.3. Winter wheat grain protein concentration response to nitrogen fertilizer rates across ten site-years in Kansas.

N rate	Site-year									
	1	2	3	4	5	6	7	8	9	10
kg ha ⁻¹	g kg ⁻¹									
0	112 a	118 a	119 a	139 a	142 a	118 a	120 a	93 a	128 a	144 a
34	118 a	124 ab	124 ab	148 a	143 a	130 b	140 b	98 a	134 ab	148 ab
67	124 b	138 bc	137 bc	165 b	148 ab	139 bc	139 b	102 ab	143 ab	156 bc
101	130 bc	137 bc	142 c	170 b	152 bc	142 cd	145 bc	111 bc	146 ab	154 bc
135	137 cd	143 cd	138 c	166 b	159 c	148 cd	153 c	113 cd	152 bc	152 abc
168	139 d	145 cd	139 c	169 b	156 c	150 cd	154 c	123 e	153 bc	156 c
202	140 d	154 d	144 c	169 b	154 bc	151 c	152 c	121 de	171 c	159 c
Standard error										
	1.6	3.8	3.5	3.5	2.3	3.1	2.8	2.2	5.1	2.1
p – value										
	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Note. Values represent estimated marginal means from linear mixed models with N-rate treatment as a fixed effect and replication as a random effect. Standard errors are those associated with the estimated marginal means for each site-year. Within each column, means sharing the same letter are not significantly different at $\alpha = 0.10$ according to Sidak-adjusted pairwise comparisons. P-values are from Type III tests with the Kenward-Roger method for denominator degrees of freedom.

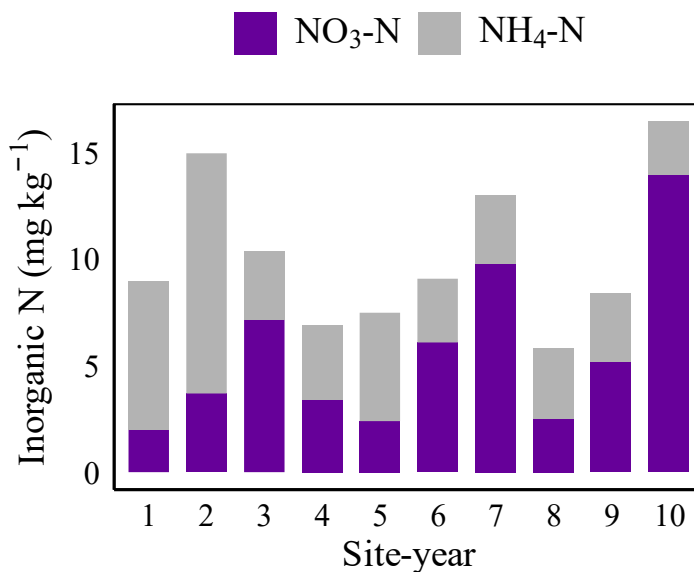


Figure 2.1. Initial soil inorganic nitrogen measured prior to planting.

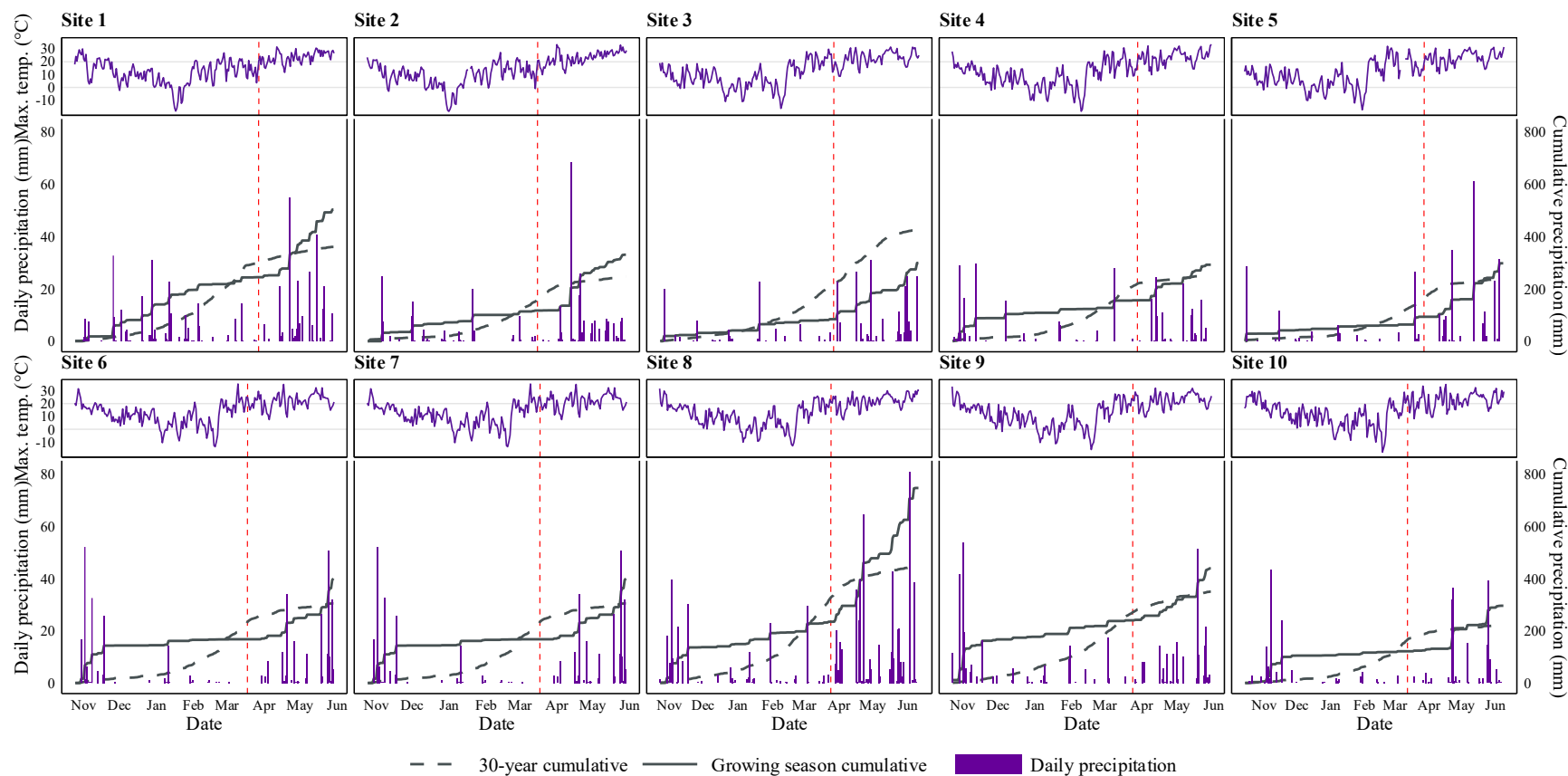


Figure 2.2. Seasonal distribution of daily precipitation, maximum air temperature, and cumulative precipitation for each site-year in Kansas.

The upper panel shows daily maximum air temperature, and the lower panel shows daily precipitation (bars), cumulative precipitation during the experimental growing season (solid line), and the 30-year average cumulative precipitation for the corresponding period (dashed line). Vertical dashed red lines indicate the timing of nitrogen fertilizer application at Feekes 6 (jointing).

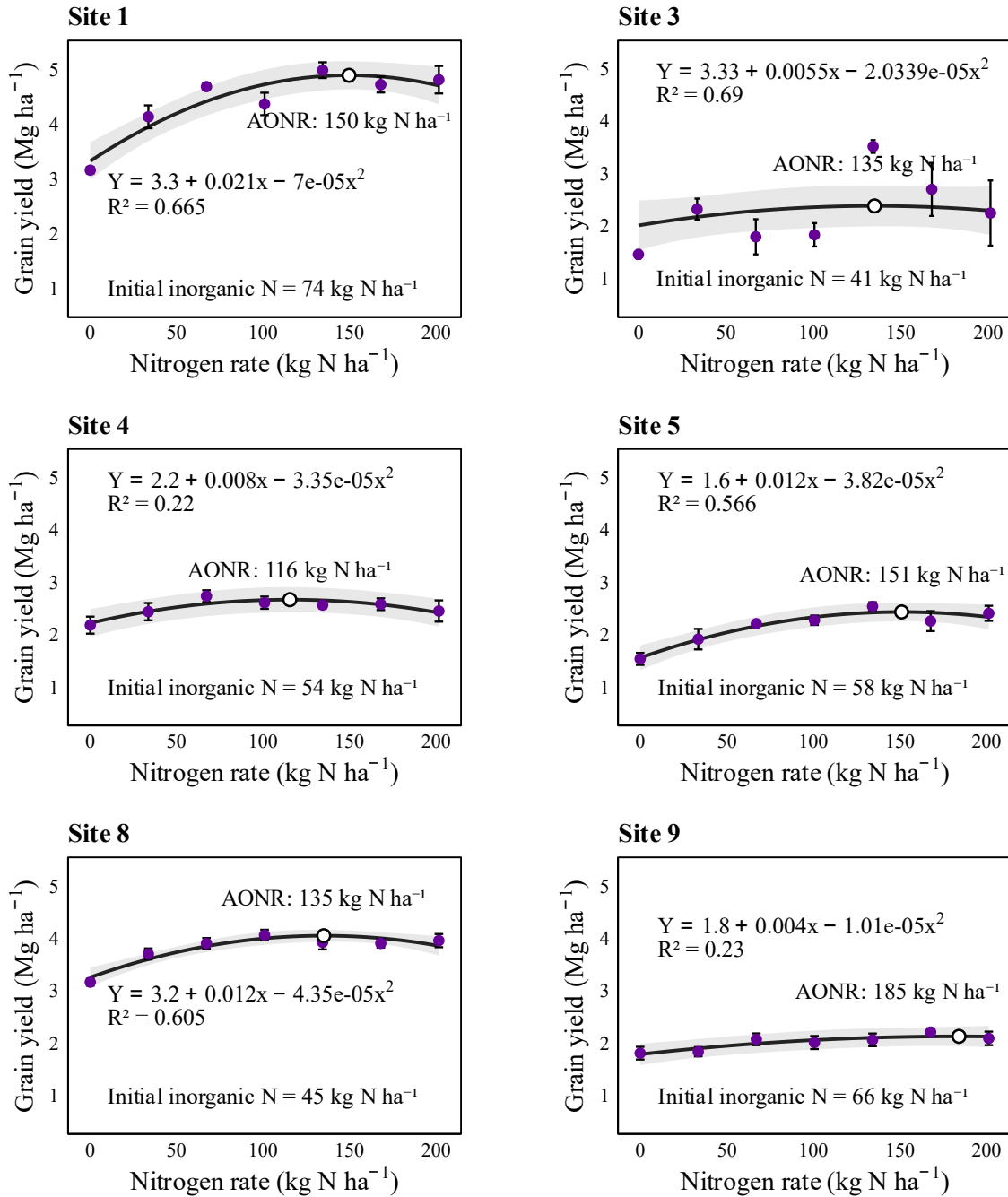


Figure 2.3. Quadratic grain yield response to nitrogen fertilizer rate and estimated agronomic optimum nitrogen rate (AONR) across six responsive site-years in Kansas.

Points represent observed mean grain yield at each N rate, and error bars indicate the standard error of the mean. Solid lines represent linear mixed model with a quadratic term with replication included as a random effect, and shaded gray areas indicate the 95% confidence interval around each fitted line. Open circles indicate the estimated AONR. R^2 values represent the marginal coefficient of determination. Inorganic N values represent pre-plant soil $\text{NO}_3\text{-N} + \text{NH}_4\text{-N}$ in the 0-60 cm soil depth.

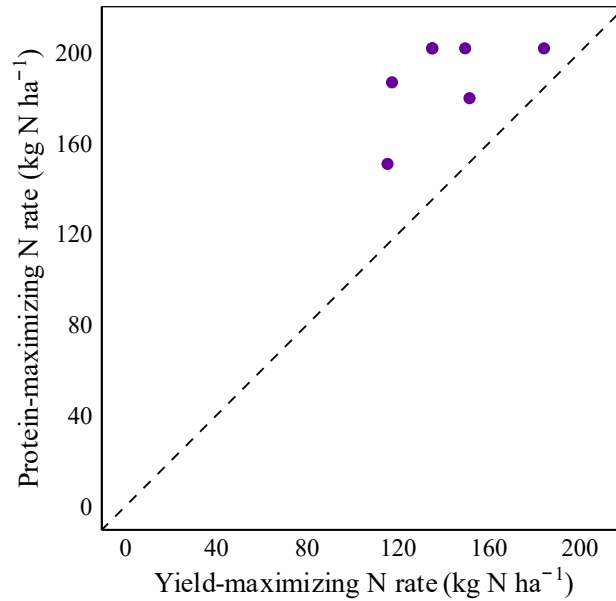


Figure 2.4. Comparison of yield-maximizing and protein-maximizing nitrogen (N) rates across responsive winter wheat site-years.

Each point represents a site-year, with N rates estimated from location-specific mixed models. The dashed 1:1 line indicates equal N requirements for maximizing grain yield and grain protein concentration. Points above the line indicate site-years where a greater N rate was required to maximize grain protein concentration than grain yield.

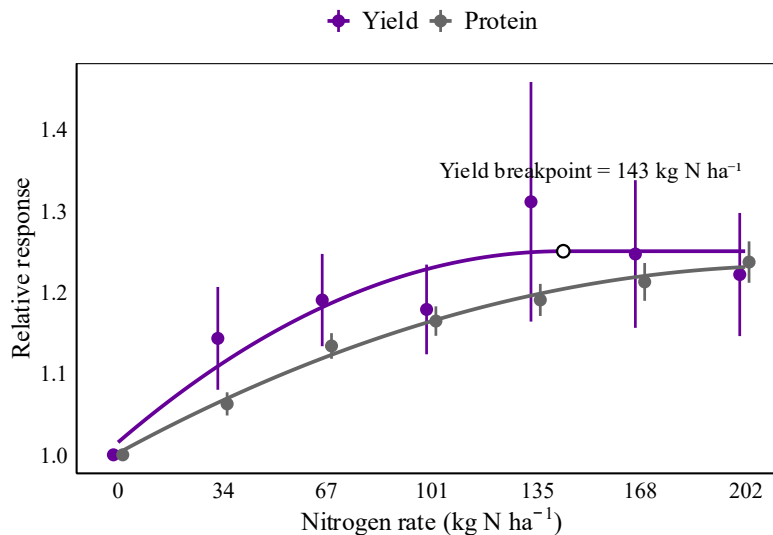


Figure 2.5. Relative grain yield and grain protein concentration responses to nitrogen (N) fertilizer across winter wheat site-years.

Points represent mean grain yield and protein responses relative to the zero-N control, averaged across site-years. Curves represent quadratic-plateau models fitted to estimated marginal means from mixed-model analyses. The open circle indicates the estimated yield breakpoint (143 kg N ha⁻¹), beyond which additional N resulted in little further increase in relative grain yield. No breakpoint was identified for grain protein concentration within the range of N rates evaluated.

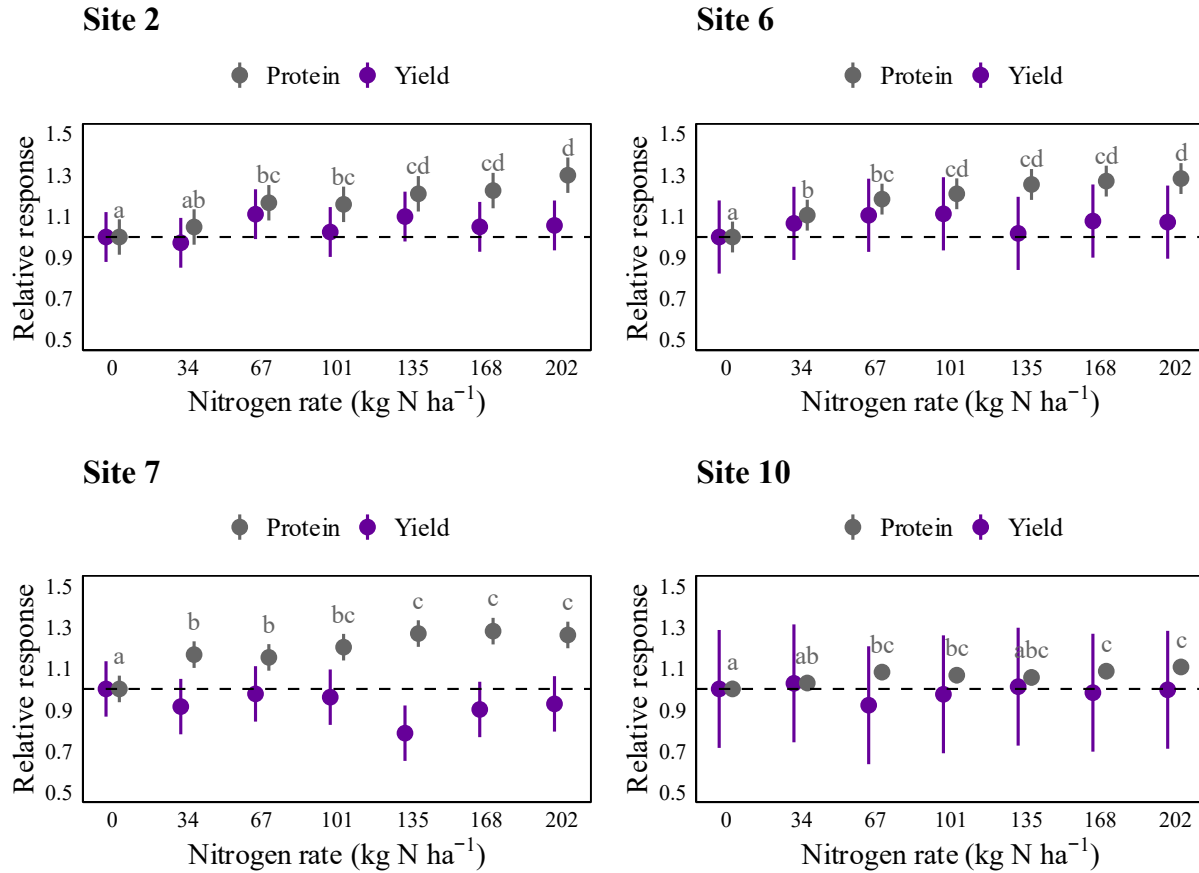


Figure 2.6. Relative grain yield and grain protein response to nitrogen fertilizer rate at four representative yield-nonresponsive site-years in Kansas. Responses are expressed relative to the estimated marginal mean of the 0 N treatment within each site-year, where 1.0 indicates the unfertilized control. Points represent relative estimated marginal means for grain yield and grain protein concentration, error bars indicate 90% confidence interval of the estimated marginal mean, and letters indicates Sidak-adjusted mean separation at $\alpha = 0.10$.

Chapter 3 - Winter Wheat Response to Nitrogen Management Strategies Across Kansas Environments

ABSTRACT

Effective nitrogen (N) management in winter wheat (*Triticum aestivum* L.) requires balancing grain yield, grain protein concentration, and N use efficiency (NUE) across diverse environments. The objective of this study was to evaluate the effectiveness of various N management strategies under a constant rate of 67 kg N ha⁻¹, relative to a site-specific expected response. Ten site-year field experiments were conducted across Kansas' diverse climate from the 2023-2024 and 2024-2025 growing seasons under no-till, rainfed conditions. Management treatments differed in N source, application timing, placement, and inhibitor use. At each site-year, separate N rate trials were also conducted and used to estimate the expected responses at 67 kg N ha⁻¹; this estimated value served as the site-specific baseline for comparing management treatments. Grain yield and agronomic efficiency (AE) were evaluated only in site-years responsive to N rate, whereas grain protein concentration and apparent recovery efficiency (ARE) were evaluated across all site-years. Management did not consistently improve grain yield, and responses were dictated by environmental conditions. Delayed application or late-season UAN sometimes reduced grain yield and AE, while split applications or inhibitor use occasionally improved both metrics under conditions favoring N loss, particularly wetter conditions. In contrast, grain protein concentration responded more consistently than grain yield. Treatments that delayed or split N application later in the season, particularly split UAN, frequently increased protein relative to the expected response, while fall or early spring applications frequently resulted in lower protein responses. Apparent recovery efficiency also

varied with management and environment, with better responses observed when N supply was more closely synchronized with crop demand. These results show that while management can affect winter wheat productivity, there is no universal strategy that performs optimally across all environments. Instead, the agronomic value of N management practices in Kansas winter wheat depends primarily on annual and local climate conditions, which affects N availability, crop demand, and N losses.

INTRODUCTION

Winter wheat (*Triticum aestivum* L.) is one of the most important crops produced in Kansas, accounting for approximately 18% of total United States production (USDA-FAS, 2025). Nitrogen (N) is the primary nutrient driving winter wheat productivity, directly influencing tiller formation, leaf development, photosynthetic activity, and grain fill (Havlin et al., 2016). However, the efficiency of N fertilizer is often compromised by one of the many N loss pathways such as ammonia volatilization, nitrate leaching, and denitrification. These losses represent not only diminished economic return for producers but also a significant environmental risk (Havlin et al., 2016). For this reason, identifying N management practices that improve fertilizer efficiency is essential for developing a more sustainable wheat production system.

The success of N fertilizer management depends on synchronization, meaning that nutrient availability should align with the crop's physiological demand. In winter wheat, N demand varies throughout the growing season with a significant portion of total plant N accumulation occurring prior to flowering (De Oliveira Silva et al., 2021). However, the risk of environmental loss is present from the moment of application. These losses are strongly affected by soil texture, drainage, and rainfall patterns. Effective N management must consider field-specific conditions when choosing the N rate, source, placement, and timing to better align N supply with what the crop needs and reduce the chances of N loss.

Several approaches have been developed to evaluate the success of fertilizer management, including different methods for calculating NUE (Fixen et al., 2014). While grain yield is commonly used to guide N management decisions, yield alone does not necessarily correspond to improvements in NUE or grain quality. Grain protein concentration is also an important indicator in winter wheat because it directly influences grain marketability and milling

value (Latshaw et al., 2016), yet protein and yield do not always respond similarly to N inputs. A common challenge in wheat is the dilution effect, where higher yields can be associated with lower grain protein concentration because grain production increases faster than the plant can accumulate N in the grain (Fowler, 2003; Justes et al., 1994). Therefore, evaluating multiple productivity indicators including grain protein concentration and NUE, is essential to fully assess how N management strategies affect both agronomic performance and fertilizer efficiency.

While tools such as split applications and inhibitors are intended to improve N management, crop responses to these practices remain inconsistent (Ballagh et al., 2025; Habibullah et al., 2018; Mohammed et al., 2013). Split applications aim to better synchronize N supply with crop demand, whereas inhibitors reduce specific N loss pathways. For example, nitrification inhibitors can reduce losses in wet, poorly drained soils, while urease inhibitors often have limited benefit in dryland systems where N loss potential is low (Mohammed et al., 2016a). It is difficult to determine whether a response is due to the amount of N applied or how it was managed because the N rate required to achieve maximum yield varies across environments (Aula et al., 2021b; Cui et al., 2006).

In Kansas, this challenge is magnified by a significant agroclimatic gradient, ranging from the high-precipitation and moderate pH of the east to the semi-arid, high-pH soils of the west. This variability, particularly regarding heat stress and rainfall timing, makes it difficult to predict whether a specific technology will consistently provide a benefit or whether the local environmental conditions will override the management choice (Lollato et al., 2019). While individual tools have been well-studied, limited research exists regarding how combinations of source, timing, and inhibitors perform together across these diverse conditions. Understanding

how these factors work together is necessary to move beyond standardized applications toward more reliable, site-specific N strategies.

Furthermore, as the largest winter wheat-producing state in the United States, Kansas presents a critical landscape for N research. Yet, relatively limited research has evaluated constant N rate management strategies across the diverse site-years that represent the environmental variability of the state. As a result, uncertainty remains about how fertilizer source, application timing and placement, and inhibitors interact with soil and climatic conditions to influence grain yield, grain protein concentration, and NUE when the N rate is held constant. Consequently, evaluating N management strategies that optimize fertilizer recovery and improve winter wheat production systems is necessary. The objective of this study was to evaluate whether N management strategies applied at a constant rate of 67 kg N ha⁻¹ altered grain yield, grain protein concentration, and N-use efficiency relative to the site-specific expected response across ten site-years in Kansas.

MATERIALS AND METHODS

Sites and Experimental Design

Ten site-year field experiments were established across Kansas during the 2023–2024 and 2024–2025 winter wheat growing seasons (Table 3.1). These site-years represented diverse environmental conditions, including variations in precipitation and soil properties. Experiments were conducted at university research stations under no-till, rainfed conditions. Agronomic practices, including cultivar selection, pesticide application, and crop rotation, varied among research stations according to local management practices.

Precipitation and maximum air temperature data were obtained from the Kansas Mesonet weather station nearest to each experimental site. Seasonal precipitation was calculated as

cumulative rainfall from sowing to the soft dough growth stage for each site-year to represent the winter wheat growing season. Long-term precipitation was expressed as the 30-year average cumulative precipitation for the corresponding sowing-to-soft-dough period at each location, based on historical records (Kansas Mesonet, 2026). Daily precipitation, cumulative precipitation, and daily maximum air temperature were used to characterize environmental conditions throughout the growing season.

At each site-year, treatments were arranged in a randomized complete block design with four replications. Nitrogen management treatments were evaluated at a constant rate of 67 kg N ha⁻¹ and differed in fertilizer source, application timing, placement, and inhibitor use (Table 3.2). The constant rate was used to provide a common basis for comparing management strategies across contrasting environments. During the 2023–2024 growing season, seven management treatments were included, while three additional fall-applied treatments were added during the 2024–2025 growing season, resulting in a total of ten management treatments.

Wheat growth stages were identified according to the Feekes scale (Large, 1954).

Inhibitors used in these treatments included: (1) SuperU, a commercially formulated urea fertilizer containing both the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT), and the nitrification inhibitor dicyandiamide (DCD), applied without additional mixing; (2) the urease inhibitor Agrotain® (NBPT), applied at rates of 2.1 mL kg⁻¹ of urea and 1.24 mL L⁻¹ of urea ammonium nitrate (UAN); and (3) the nitrification inhibitor Centuro® (pronitridine), which was applied at 12 mL L⁻¹ of UAN.

Nitrogen application timings included fall, Feekes 6, Feekes 7, and split applications between Feekes 6 and Feekes 10.5. Split treatments differed in fertilizer source and N

distribution between timings and were included to evaluate how delayed N application influenced winter wheat response under contrasting environmental conditions.

Additional N rate treatments were established at each site-year, ranging from 34 to 202 kg N ha⁻¹, to develop site-specific N response curves. These trials were used to estimate the expected response at 67 kg N ha⁻¹ for each site-year, based on a baseline application of urea (46-0-0) broadcast at Feekes 6. These N rate treatments were not included in the statistical comparisons of management strategies presented in this chapter; rather, they were used to define the site-specific baseline response against which the constant-rate management treatments were compared.

Soil and Plant Sampling and Analysis

Composite soil samples were collected by block prior to sowing and fertilizer application to determine initial fertility status. At the 0–15 cm depth, each composite sample consisted of 10 to 12 cores collected using a 1.9-cm-diameter probe. At the 0–60 cm depth, each composite sample consisted of 4 to 5 cores. All soil samples were oven-dried at 40°C to a constant weight, ground, and passed through a 2-mm sieve before analysis.

Soil samples were analyzed at the Kansas State University Agronomy Soil Testing Laboratory. Samples collected at the 0-15 cm depth were used to determine: (1) soil pH, using a 1:1 soil-to-water method; (2) soil organic matter, via the Loss on Ignition; (3) plant available P, using a Mehlich-3 extraction; and (4) exchangeable K, Ca, Mg, and Na, using ammonium acetate extraction. Micronutrients, including Fe, Zn, Cu, and Mn, were extracted using the DTPA method, following procedures described by Brown (1998).

Soil samples collected at the 0-60 cm depth were analyzed for inorganic N (nitrate-N and ammonium-N) using 1 M potassium chloride (KCl) extraction (Brown, 1998). Extractable sulfur

was determined using a monocalcium phosphate extraction. Soil series for each location were identified using the USDA Web Soil Survey (USDA-NRCS, 2006). Selected pre-plant soil chemical properties used to characterize the experimental environments are summarized in Table 3.1.

Aboveground biomass was sampled at the soft dough growth stage (Feekes 11.2) to quantify total plant N uptake for the calculation of Apparent Recovery Efficiency (ARE). Plant material was clipped at ground level from two rows near the center of each plot, representing a total sampled area of approximately 0.45 m². Samples were weighed fresh in the field, mechanically chopped, and subsampled. Subsamples were weighed, oven-dried at 60°C to a constant weight and used to estimate dry matter concentration. Total aboveground dry biomass was calculated based on fresh and dry subsample weights as follows:

$$Total\ dry\ biomass = \frac{Dry\ subsample\ mass}{Fresh\ subsample\ mass} \times Total\ fresh\ biomass.$$

Dried biomass samples were ground using a Wiley benchtop cutting mill (Thomas Scientific, Swedesboro, NJ, USA) and analyzed for total N concentration by dry combustion. Total aboveground plant N uptake was calculated as the product of dry biomass and tissue N concentration and was used to estimate ARE.

Grain yield was determined by harvesting the central portion of each plot using a small plot combine. Harvested grain weight was recorded for each plot, and grain moisture was measured using a GAC 2500-AGRI grain analysis computer (Dickey-John, Auburn, IL, USA). Grain yield was standardized to a 13.5% moisture basis.

Grain protein concentration was determined on a whole-grain basis using a DS3 near-infrared spectrometer (FOSS Analytical, Hillerød, Denmark), utilizing the FOSS wheat calibration, with output expressed in g kg⁻¹.

Statistical Analysis

All analyses were conducted in R (version 4.4.0; R Core Team, 2024) using linear mixed-effects models fitted with the ‘lme4’ (Bates et al., 2015) and ‘lmerTest’ (Kuznetsova et al., 2017) packages.

A two-step approach was used to evaluate N management treatment responses relative to the site-specific expected response at 67 kg N ha⁻¹. This approach was designed to address two questions: (i) what was the expected response to 67 kg N ha⁻¹ at each site-year, and (ii) did a given management treatment perform above or below that expected response?

First, site-years were classified as responsive or nonresponsive to N rate based on the significance of the N rate effect within each site-year ANOVA ($p < 0.10$). For responsive site-years, site-specific expected values were estimated using the N rate treatments. Mixed-effects models were fitted separately for each site-year with N rate as a fixed effect and replication as a random effect. Depending on the site-year, the functional form of the N rate response included linear or quadratic terms, and for one site-year (Site 3), plot position was included as an additional covariate to account for within-site variation. The fitted models were then used to predict the expected response at 67 kg N ha⁻¹, and this model-predicted value was used as the site-specific baseline for comparison with the N management treatments.

Second, for the N management treatments, responses were expressed as the difference between observed values and the corresponding site-specific expected value. These difference variables were analyzed within each site-year using linear mixed-effects models with treatment as a fixed effect and replication as a random effect.

Estimated marginal means for each treatment were obtained using the ‘emmeans’ (Lenth & Piaskowski, 2017) package with the Kenward–Roger (Kenward & Roger, 1997) method for

denominator degrees of freedom. Ninety percent confidence intervals were used to assess treatment responses relative to the expected value. Treatment responses were interpreted based on whether the 90% confidence interval included zero. Positive and negative values indicated responses above or below the expected response at 67 kg N ha⁻¹, respectively.

Nitrogen use efficiency metrics, which describe how efficiently applied fertilizer N contributes to crop production or is recovered in plant uptake, depending on the metric used (Fixen et al., 2014), were calculated at the plot level for the management treatments. Agronomic efficiency, defined as the increase in grain yield per unit of applied N, was calculated to assess crop response to N and evaluate the efficiency of management practices:

$$AE = \frac{Y - Y_0}{F},$$

where Y is the grain yield of the fertilized plot, Y₀ is the grain yield of the corresponding 0 N treatment within the same replication, and F is the amount of fertilizer N applied.

Apparent recovery efficiency, defined as the proportion of applied N recovered in aboveground plant biomass, was calculated to indicate the potential for nutrient loss from the cropping system and to assess the efficiency of management practices:

$$ARE = \frac{U - U_0}{F} \times 100,$$

where U is the total aboveground plant N uptake in the fertilized plot and U₀ is the total plant N uptake in the corresponding 0 N treatment. Consistent with Fixen, et al. (2014), AE was used as a short-term indicator of the productivity gain obtained per unit of applied N, while ARE was used to quantify the proportion of applied N recovered in plant uptake and to indicate the potential for N loss from the cropping system.

Analyses of grain yield and AE relative to the site-specific expected response were limited to site-years classified as responsive to the N rate. In contrast, grain protein concentration and ARE were evaluated across all site-years.

RESULTS AND DISCUSSIONS

Environmental Characterization

The experimental sites represented a diverse range of agroclimatic conditions across Kansas, covering significant gradients in both precipitation and soil properties (Table 3.1; Figure 3.1; Figure 3.2). The 30-year mean growing season precipitation for the sowing-to-soft-dough period at each location, calculated from Kansas Mesonet records for 1994-2023, ranged from 246 mm to 518 mm (Kansas Mesonet, 2026). During the experimental period, cumulative growing season precipitation followed a similar pattern, with Site 4 receiving the least rainfall (293 mm) and Site 8 receiving the greatest (746 mm). This precipitation gradient provides important context for interpreting site-level differences in winter wheat performance, as yield and yield gaps in Kansas are frequently associated with water availability and climate conditions (Jaenisch et al., 2021). Water availability also influences N uptake and crop metabolic activity, which affects fertilizer responsiveness across environments (Zhao et al., 2024).

In addition to differences in cumulative precipitation, the timing and distribution of rainfall events varied among site-years, while seasonal temperature patterns were generally similar across environments (Figure 3.2). Because this study evaluated differences among N management strategies, these contrasting weather patterns provided important context for interpreting the effectiveness of fertilizer source, application timing, and inhibitor use under varying environmental conditions.

Initial soil properties also varied across site-years, likely contributing to differences in crop response to N fertilization. Soil organic matter ranged from 23 g kg⁻¹ to 34 g kg⁻¹, while soil pH ranged from strongly acidic (5.1) to moderately alkaline (7.9).

Initial soil fertility varied among environments. Total inorganic N (NO₃⁻-N + NH₄⁺-N) ranged from 5.8 mg kg⁻¹ to 16.5 mg kg⁻¹. Extractable sulfate concentrations were generally low, ranging from 2.1 mg kg⁻¹ to 24 mg kg⁻¹. Soil phosphorus (P) and potassium (K) also varied widely, with extractable P ranging from 12 mg kg⁻¹ to 72 mg kg⁻¹, and exchangeable K from 141 mg kg⁻¹ to 516 mg kg⁻¹.

Together, these site-years provided a strong environmental gradient, creating a useful basis for evaluating winter wheat responses to constant N rate management across Kansas environments.

Nitrogen Management Effects on Grain Yield and Agronomic Efficiency

Nitrogen management effects on grain yield and AE were evaluated as deviations from the site-specific expected response at 67 kg N ha⁻¹ across yield-responsive site-years (Figure 3.3; Figure 3.4). Most management treatments were not different from the expected response, indicating that changes in N source, timing, placement, or inhibitor use did not consistently alter crop performance at the constant N rate. However, several treatments resulted in positive or negative deviations at individual site-years, demonstrating that the effectiveness of a given management strategy may depend on local environmental conditions.

A clear example was observed at Site 1, where Treatment 7 (F7 SuperU) was 0.95 Mg ha⁻¹ below the expected response and 14.2 kg grain kg⁻¹ N below the expected AE response. This pattern suggests that delaying N application until Feekes 7 may have reduced the opportunity to support earlier yield-forming processes, such as tiller retention and spike development, which are

more strongly influenced by N availability earlier in the season (Aula et al., 2021b; Ruiz Diaz & Lollato, 2021), as suggested by Simão et al. (2024). Although late N applications can benefit grain quality (Giordano et al., 2023), the results presented indicate that, at Site 1, delayed application was detrimental to both grain yield and AE.

In contrast, positive grain yield deviations were observed at Sites 3 and 9, particularly in treatments that included inhibitor use or split applications. This suggests that practices designed to slow N release or improve its temporal distribution may have contributed to performance above the site-specific expected response. However, this pattern was more consistent for AE at Site 9 than at Site 3. At Site 9, several of these treatments also resulted in significantly positive AE deviations, indicating that increasing yields were accompanied by more efficient use of applied N.

The contrast between Sites 3 and 9 suggests that the agronomic value of these management strategies depended on environmental conditions. Site 9 received more precipitation during the growing season than Site 3 (439 vs. 299 mm). Site 9 had a slightly lower pre-plant inorganic N (8.4 vs. 10.4 mg kg⁻¹), conditions under which the protection of applied N was more likely to influence crop response. Urease inhibitors, such as NBPT, delay urea hydrolysis, whereas nitrification inhibitors delay the conversion of ammonium to nitrate; together, these mechanisms reduce fertilizer N losses through volatilization, leaching, and denitrification. Under environments where loss risk is elevated, these effects can improve NUE, although responses remain strongly dependent on site conditions (Abalos et al., 2014; Aula et al., 2021b).

The contrasting patterns observed at Sites 8 and 4 further highlight the importance of site-specific risk in management decisions. At Site 8, seasonal precipitation reached 746 mm, representing the highest rainfall among all site-years (Figure 3.2). In this high-loss environment,

some treatments utilizing inhibitors yielded higher than the baseline. This suggests that in high-moisture environments, these technologies may provide a significant advantage, whereas at Site 4, no management strategy consistently outperformed the expected response. Notably, the contrast at Site 8 between fall urea (-0.38 Mg ha^{-1}) and fall urea + NBPT ($+0.41 \text{ Mg ha}^{-1}$) provides strong evidence that inhibitor technology can successfully mitigate the risks of early-season N loss, effectively convert a yield penalty into a yield gain, a response that was also consistent with the AE results (Abalos et al., 2014; Mohammed et al., 2016).

The performance of Treatment 5 (split UAN) provides an additional example of how management outcomes depended on application strategy and site conditions. This treatment was below the expected response for both grain yield and AE at most site-years; this was most evident at Sites 5 and 6, with deviations of -0.28 and -0.58 Mg ha^{-1} for yield and -4.16 and $-8.96 \text{ kg grain kg}^{-1} \text{ N}$ for AE, respectively. Field observations at these sites indicated visible leaf burn symptoms following the second UAN application at flowering, suggesting that localized fertilizer injury may have reduced crop performance. Although this response was not directly quantified, it is consistent with the observed negative deviations and indicates that late-season UAN application can introduce the risk of crop injury under certain conditions (Dick et al., 2016; Woodard & Bly, 1998).

The response of fall-applied treatments further illustrates the importance of environmental context. These treatments were not universally detrimental, and in some cases, they performed favorable relative to the expected response. At Site 9, fall-applied urea with NBPT (Treatment 10) produced greater yield and AE responses than the expected response, while fall-applied urea without inhibitor (Treatment 8) resulted in lower responses. This contrast suggests that inhibitor protection improved the performance of fall-applied N under these

conditions. This contrast is consistent with the role of urease inhibitors in delaying urea hydrolysis and reducing early-season N losses, particularly when fertilizer must persist in the soil prior to crop uptake (Abalos et al., 2014).

These results indicate that constant N rate management strategies can influence crop performance relative to the site-specific expected response, but their effectiveness was not consistent across all environments. The agronomic value of fertilizer source, timing, split application, and inhibitor use depended on how each practice interacted with site-year conditions affecting N availability, loss potential, and crop demand. No single management strategy provided a consistent advantage across all responsive environments.

Grain Protein Response Relative to the Site-Specific Expected Response

Grain protein concentration responded more consistently to N management than grain yield. Across site-years, more treatments differed from the site-specific expected response at 67 kg N ha⁻¹ for grain protein concentration than for grain yield (Figure 3.5). This indicates that N management had a stronger influence on grain N accumulation than on grain yield production at the constant N rate.

A consistent positive response pattern was observed for treatments that involved delayed or split N application. The magnitude of this response was most pronounced for Treatment 5 (split UAN), which showed positive results in nearly all site-years. At sites with high initial inorganic N, such as Site 10 (16.5 mg kg⁻¹), where grain yield response was limited, split-applying UAN resulted in a protein increase of 5.8 g kg⁻¹. These results suggest that providing N closer to reproductive stages enhanced grain N accumulation. This is consistent with the role of late-season N in supporting grain protein formation. As N is applied closer to grain fill, it is more likely to be transported directly to the grain rather than contributing to vegetative growth (Aula

et al., 2021; Giordano et al., 2023). Bogard et al. (2010) also reported that grain protein concentration in wheat is strongly associated with post-anthesis N uptake, even when yield response is limited.

In contrast, treatments involving early-season N applications that did not involve split applications generally resulted in negative protein responses, similar to previous reports in the region (Lollato et al., 2021). Fall-applied treatments (8, 9, and 10) were most often below the site-specific expected response, with negative deviations observed at several locations, including Sites 3, 6, 8, and 9. This pattern suggests that fall-applied N was often less effective for supporting grain protein concentration, likely because N availability was not sustained to support reproductive growth.

Similarly, spring-applied UAN treatments at Feekes 6 (Treatments 3 and 4) frequently produced negative deviations across site-years, regardless of inhibitor inclusion. In contrast, urea-based treatments applied at the same timing (Treatments 1 and 2) generally showed more neutral or slightly positive responses. This pattern suggests that the N source may have influenced the effectiveness of early-season application for grain protein formation. One possible explanation is that UAN applied to the surface under no-till conditions may have interacted with crop residues, potentially reducing immediate N availability through temporary immobilization or limited soil contact. Previous studies have shown that surface-applied UAN can perform less favorably in residue-rich no-till systems (Mengel et al., 1982; Stecker et al., 1993), and that residue decomposition can temporarily reduce plant-available N (Recous et al., 1995). While surface residue mass was not directly measured, all sites were managed under no-till systems. Ruiz Diaz et al. (2026) noted that liquid UAN is more prone to being intercepted by surface

residues compared to granular urea, which can more effectively reach the soil surface in Kansas cropping systems.

Patterns of grain yield and grain protein concentration were not uniform across treatments and site-years. In some cases, grain yield and grain protein concentration responded in opposite directions within the same treatment-site combination, as observed for Treatment 7 at Site 1 and Treatment 5 at Site 6 (Figure 3.5). In these instances, protein concentration increased despite negative yield deviations. This inverse relationship is often attributed to the dilution effect, where environmental or management-induced limitations on yield result in a higher concentration of accumulated N per unit of grain (Fowler, 2003).

Conversely, at Site 9, the observation that both responses (yield and protein) were positive for several treatments, suggests that improved N management under favorable conditions supported both productivity and grain protein accumulation. At Site 3, however, positive yield responses were paired with negative protein responses across most treatments, indicating that management can enhance productivity without necessarily increasing grain protein accumulation. Together, these patterns suggest that grain yield and grain protein responded to N management through different mechanisms, and that the degree to which the two responses aligned depended strongly on site-year conditions and on the timing and form of N supply.

Overall, these results indicate that grain protein concentration at a constant N rate was influenced by the timing and distribution of N availability rather than by fertilizer source alone. Management strategies that redistributed N later in the growing season more consistently increased protein relative to the site-specific expected response. Fall-applied N often failed to support grain protein accumulation. These findings emphasize that N management decisions

affecting temporal N availability play a critical role in determining grain quality, even when total N rate is held constant.

Apparent Recovery Efficiency Relative to the Site Specific Expected Response

Apparent recovery efficiency provided an additional measure of treatment response relative to the site-specific expected response at 67 kg N ha⁻¹ (Figure 3.6). Overall, ARE responses varied across site-years and treatments. Both positive and negative deviations from the expected response were observed. This suggests that the effect of N management on fertilizer recovery depended on environmental conditions and on how each strategy influenced the timing and retention of available N for the crop.

Across the site-years, split application strategies performed better, although the magnitude of the response might be related to the proportion of N fertilizer supplied earlier in the season. Treatment 6 (split urea + UAN) produced some of the largest positive responses, where ARE increased by more than 30 percentage points relative to the baseline. The advantage of this treatment likely reflects the higher proportion of N applied at Feekes 6 (56 kg N ha⁻¹), which might have ensured sufficient N availability during the beginning of rapid stem elongation. This period is characterized by rapid biomass accumulation and increasing crop N demand, and maintaining high N availability at this stage is critical to support early yield-forming processes such as tiller retention and spike development (Ruiz Diaz & Lollato, 2021). By providing a greater proportion of the N during this critical demand peak while retaining a small portion for flowering (11 kg N ha⁻¹), Treatment 6 effectively synchronized N supply with the timing of crop uptake (De Oliveira Silva et al., 2021).

In contrast, Treatment 5 (split UAN), which utilized a balanced distribution of N between Feekes 6 and flowering (33.5 and 33.5 kg N ha⁻¹), showed more variable recovery. Its

lower performance relative to the baseline at some site-years suggests that split applications may have reduced the opportunity to support earlier vegetative processes during the high-demand stem elongation phase. As noted by Mohammed et al. (2016), the benefits of split applications and enhanced efficiency fertilizers are most evident when they mitigate specific environmental losses. In environments where early-season N loss risk was lower, such as the below-average rainfall conditions at Site 2, strategies that supplied more N at Feekes 6 tended to show better recovery. In this case, the baseline response and Treatment 6 likely supported greater N recovery than Treatment 5 because a larger proportion of their total N was available earlier in the stem elongation period, whereas Treatment 5 distributed N more evenly between Feekes 6 and flowering. Furthermore, delaying the entire spring N application until Feekes 7 (Treatment 7) consistently resulted in negative ARE responses, indicating that missing the window of rapid biomass accumulation can limit crop N recovery across most environments in Kansas (Ruiz Diaz & Lollato, 2021).

Site-specific response patterns further revealed the role of environmental influence on the efficiency of the management treatments. A notable pattern of negative ARE deviations was observed at Sites 1, 3, and 8, representing environments where the risk of N loss was higher or N availability was reduced. At Site 8, which received the highest seasonal precipitation (746 mm), the overall negative deviations likely reflect rainfall-driven losses such as leaching and denitrification, especially for the fall-applied treatment in the poorly drained Woodson soil series (USDA-NRCS, 2015).

Most treatments resulted in ARE above the baseline at sites 4 and 9. At Site 9, a unique situation was observed, where yield, grain protein concentration, and ARE all showed positive deviations at the same time. Rust-like symptoms were observed later in the growing season;

however, disease incidence and severity were not quantified. Therefore, the potential contribution of disease pressure to the observed responses could not be determined.

Overall, these results indicate that ARE was strongly influenced by management practices affecting N retention and timing, but these responses remained dependent on the environment

. Management strategies that improved the synchronization between N supply and crop demand tended to show better recovery. However, the lack of a single approach that worked across all environments, reinforces the importance of site-specific management decisions in Kansas wheat systems.

CONCLUSIONS

This study evaluated the effectiveness of N management strategies applied at a constant N rate of 67 kg N ha⁻¹ across ten Kansas site-years. Treatment effectiveness was assessed relative to the site-specific estimated response at 67 kg N ha⁻¹ using grain yield, grain protein concentration, AE, and ARE. These results demonstrated that alternative N source, timing, placement, and inhibitor use did not consistently improve winter wheat performance relative to the expected response. Instead, treatment effectiveness was strongly dependent on environmental conditions, particularly those influencing N loss risk and crop demand.

Across the site-years classified as responsive to N rate, grain yield generally showed limited response across treatments. Practices such as delaying spring N application until Feekes 7 or applying split UAN later in the season more often resulted in negative response, likely due to reduced support of early yield-forming processes or increased risk of crop injury. In contrast, strategies involving inhibitors or split applications more often improved yield in environments with greater potential for N loss, particularly under wetter conditions.

Grain protein concentration responded more consistently to N management than grain yield, reflecting its greater sensitivity to changes in N availability. Management strategies that included delayed or split applications later in the season consistently increased protein relative to the expected response. In contrast, fall or earlier spring applications often resulted in lower protein concentrations, indicating that N availability was not sustained throughout the reproductive period. These results reinforce that grain protein is highly sensitive to the temporal distribution of available N.

Apparent recovery efficiency and AE provided additional insight into treatment performance by capturing how effectively applied N was utilized by the crop. In general, management strategies that improved synchronization between N supply and crop demand enhanced N recovery, particularly when sufficient N was available during early vegetative growth stages to support tiller retention. However, similar to grain yield, AE and ARE responses were highly environment-dependent, with no consistent pattern across all site-years.

Taken together, these findings indicate that the agronomic value of N management strategies at a constant rate was primarily determined by their interaction with site-specific conditions, including precipitation patterns, soil properties, and potential N loss pathways. Therefore, improving N management in Kansas winter wheat systems requires a site-specific approach that considers environmental risk factors rather than a universal recommendation.

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TABLES AND FIGURES

Table 3.1. Site-years information including crop management, and soil properties measured before planting for winter wheat experiments in Kansas.

Sites-years	Growing season	County	Soil series ^a	Subgroup ^b	Texture class	Previous crop	Variety	Planting date	pH	OM
										g kg ⁻¹
1	2023-2024	Riley	Bismarckgrove	FL. Hapludolls	Silt loam	Soybean	KS Providence	10/16/2023	6.9	27
2	2023-2024	Republic	Crete	PU. Argiustolls	Silty clay loam	Soybean	KS Ahearn	11/07/2023	5.3	25
3	2024-2025	Riley	Bismarckgrove	FL. Hapludolls	Silt loam	Soybean	KS Mako	11/16/2024	6.5	25
4	2024-2025	Republic	Crete	PU. Argiustolls	Silty clay loam	Soybean	KS Mako	10/29/2024	5.8	27
5	2024-2025	Republic	Crete	PU. Argiustolls	Silty clay loam	Soybean	KS Mako	11/17/2024	5.1	27
6	2024-2025	Reno	Nalim	UD. Argiustolls	Clay loam	Soybean	KS Providence	10/25/2024	7.6	24
7	2024-2025	Reno	Darlow	V. Natrustalfs	Clay loam	Soybean	KS Providence	10/25/2024	5.2	26
8	2024-2025	Franklin	Woodson	AB. Argiaquolls	Silty clay loam	Soybean	KS Providence	10/24/2024	6	32
9	2024-2025	Shawnee	Bismarckgrove	FL. Hapludolls	Loam	Soybean	Doublestop CL Plus	10/24/2024	6.7	23
10	2024-2025	Ellis	Roxbury	CU. Haplustolls	Silty clay loam	Wheat	Joe	10/15/2024	7.9	34

Note. All soil samples were collected prior to planting at a depth of 0–15 cm for soil analyses.

OM, organic matter; AB, Abruptic; CU, Cumulic; FL, Fluventic; PU, Pachic Udertic; UD, Udic; V, Vertic.

^aSource: Web Soil Survey.

^bSource: USDA-NRCS Official Soil Series Descriptions.

Table 3.2. Nitrogen Management Treatment Evaluated Across Kansas Research Stations (2023-2025).

Treatments	N rate	Fertilizer source	N analysis	Inhibitor type	Active ingredient	Application timing	Application method	Growing seasons
	kg ha ⁻¹		N-P ₂ O ₅ -K ₂ O					
1	67	SuperU	46-0-0	Dual	NBPT 0.06% & DCD 0.85%	Feekes 6	Broadcast	2023-2025
2	67	urea	46-0-0	Urease	NBPT 30%	Feekes 6	Broadcast	2023-2025
3	67	UAN	28-0-0	-	-	Feekes 6	Stream	2023-2025
4	67	UAN	28-0-0	Dual	NBPT 30% & Pronitridine 14%	Feekes 6	Stream	2023-2025
5 ^a	67	UAN	28-0-0	—	—	Feekes 6 & Feekes 10.5	Stream	2023-2025
6 ^b	67	urea & UAN	46-0-0 & 28-0-0	—	—	Feekes 6 & Feekes 10.5	Broadcast & Stream	2023-2025
7	67	SuperU	46-0-0	Dual	NBPT 0.06% & DCD 0.85%	Feekes 7	Broadcast	2023-2025
8	67	urea	46-0-0	—	—	Fall	Broadcast	2024-2025
9	67	SuperU	46-0-0	Dual	NBPT 0.06% & DCD 0.85%	Fall	Broadcast	2024-2025
10	67	urea	46-0-0	Urease	NBPT 30 %	Fall	Broadcast	2024-2025

Note. N = Nitrogen; UAN = urea ammonium nitrate; NBPT = N-(n-butyl) thiophosphoric triamide (urease inhibitor); DCD, dicyandiamide (nitrification inhibitor). SuperU, urea product with NBPT and DCD; A dash (—) indicates not applicable.

a Split applied UAN, 33.5 kg N ha⁻¹ at Feekes 6 and 33.5 kg N ha⁻¹ at Feekes 10.5

b Split applications: 56 kg N ha⁻¹ as urea at Feekes 6 and 11 kg N ha⁻¹ as UAN at Feekes 10.5.

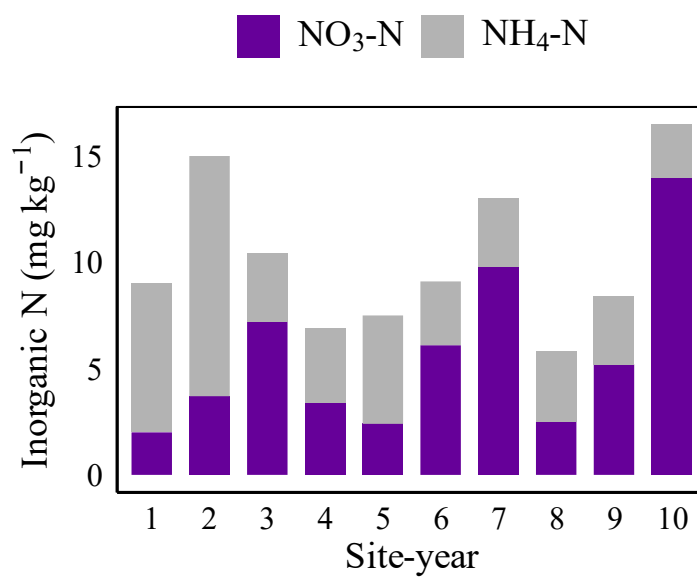


Figure 3.1. Initial soil inorganic nitrogen measured prior to planting.

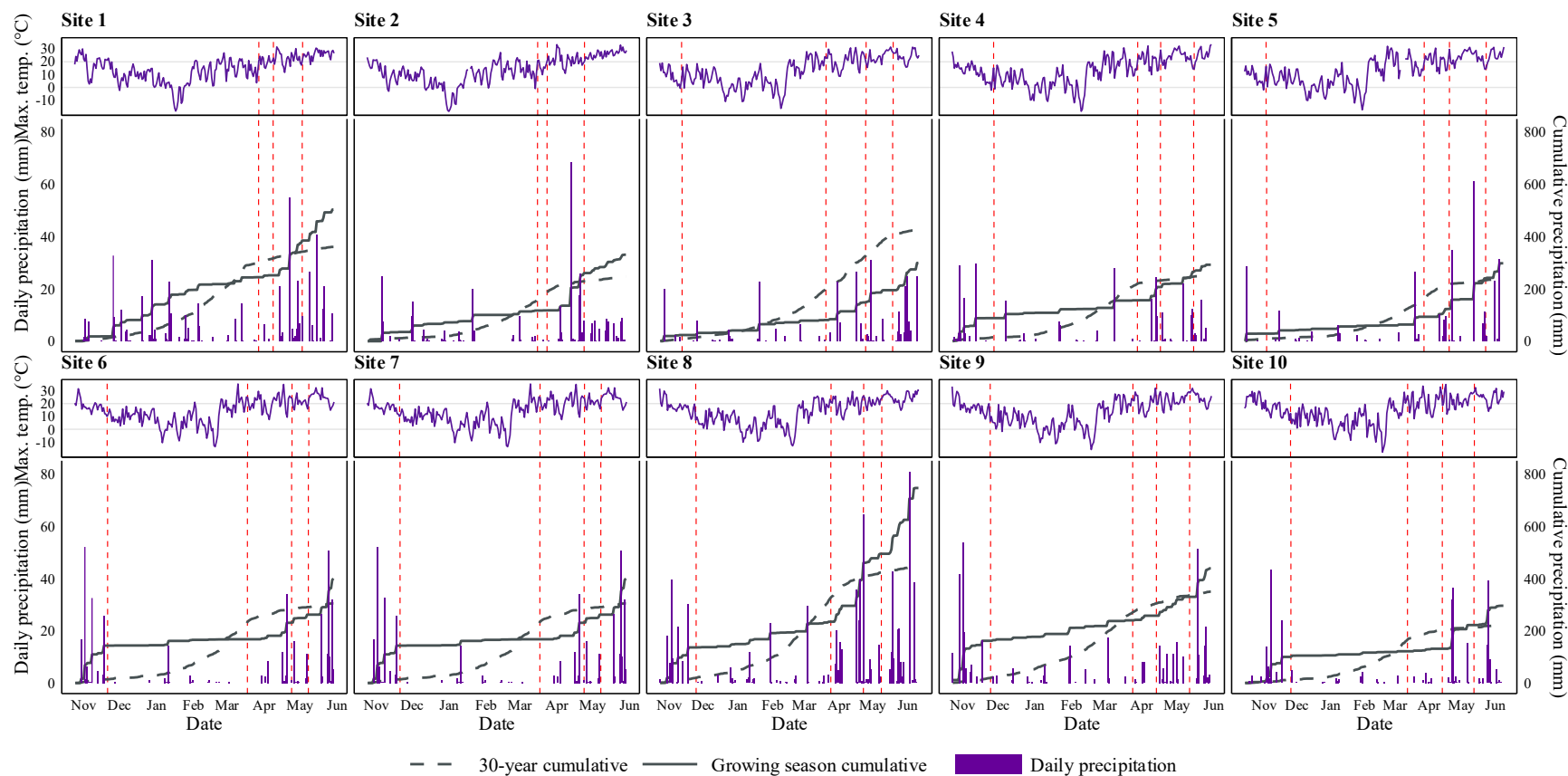


Figure 3.2. Seasonal distribution of daily precipitation, maximum air temperature, and cumulative precipitation for each site-year in Kansas.

The upper panel shows daily maximum air temperature, and the lower panel shows daily precipitation (bars), cumulative precipitation during the experimental growing season (solid line), and the 30-year average cumulative precipitation for the corresponding period (dashed line). Vertical dashed red lines indicate the timing of nitrogen fertilizer application at Fall, Feekes 6, around Feekes 7, and flowering, respectively.

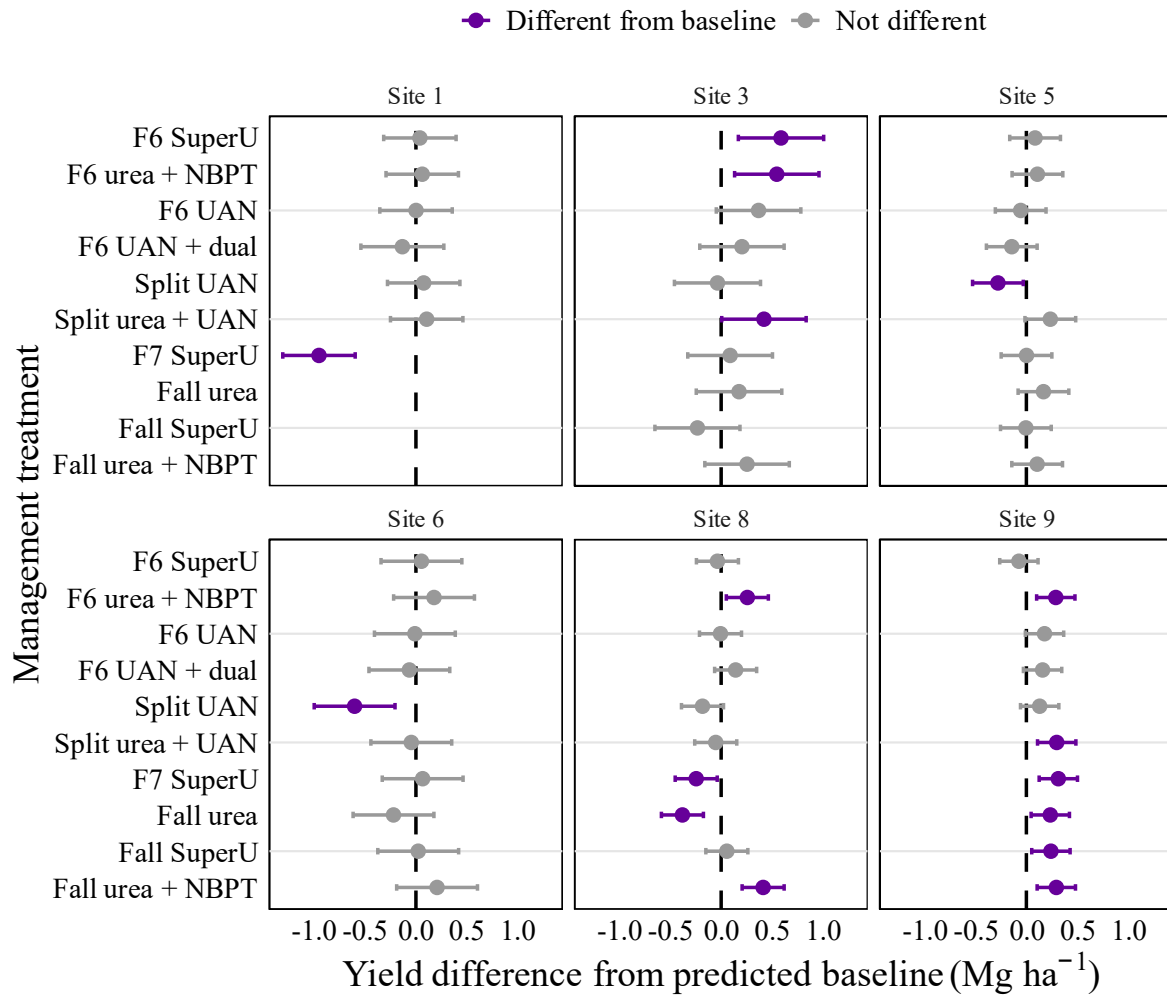


Figure 3.3. Estimated yield differences from the site-specific baseline for management treatments across yield-responsive site-years in Kansas. Points are adjusted means and horizontal bars are 90% confidence intervals. Purple points indicate treatments that differ from the baseline at the 90% confidence level. F = Feekes growth stage. Management treatments are as follows: 1, F6 SuperU; 2, F6 urea + NBPT; 3, F6 UAN; 4, F6 UAN + dual; 5, split UAN; 6, split urea + UAN; 7, F7 SuperU; 8, fall urea; 9, fall SuperU; 10, fall urea + NBPT.

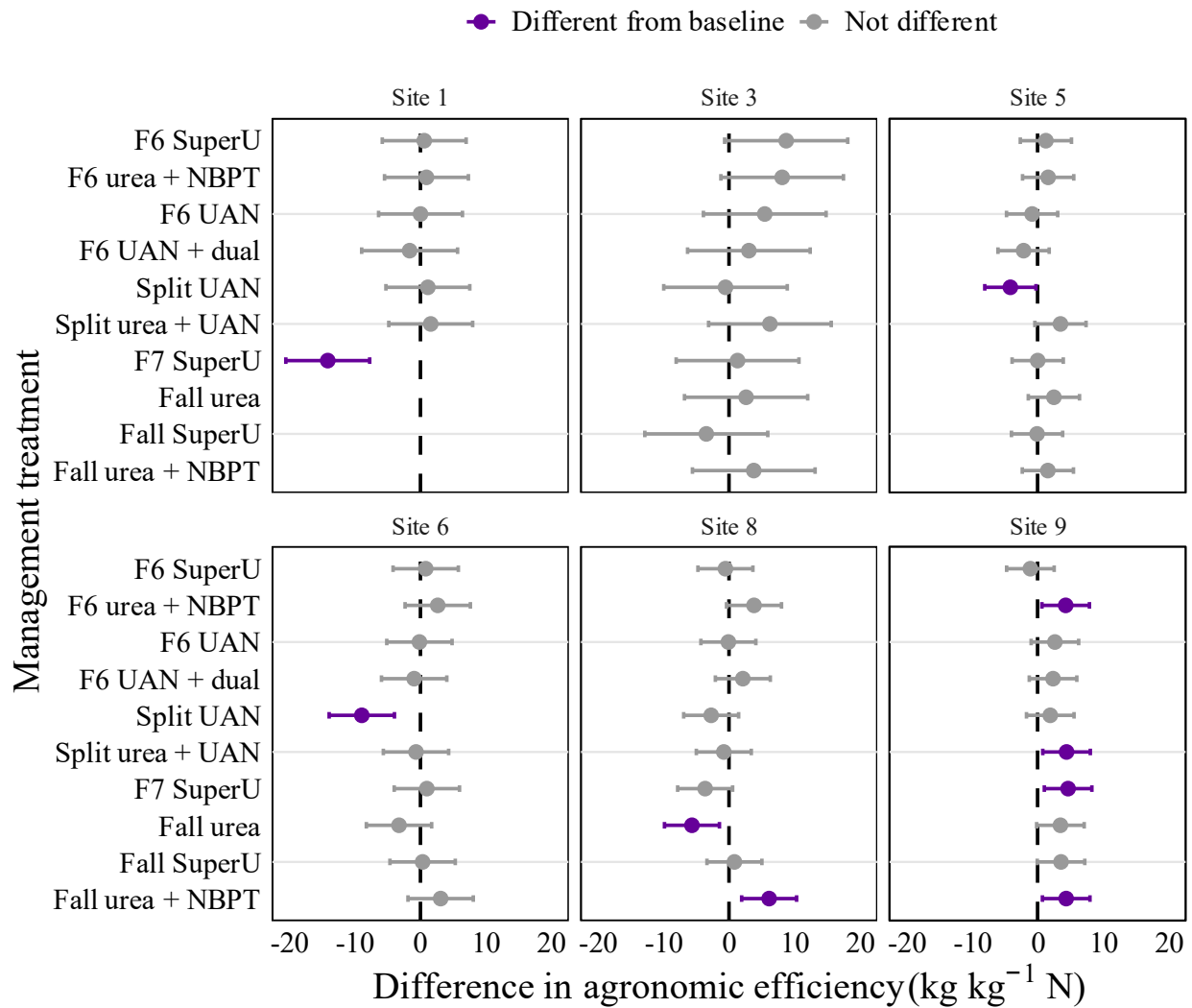


Figure 3.4. Estimated differences in Agronomic Efficiency from the site-specific baseline for management treatments across yield-responsive site-years in Kansas.

Points are adjusted means and horizontal bars are 90% confidence intervals. Purple points indicate treatments that differ from the baseline at the 90% confidence level. F = Feekes growth stage. Management treatments are as follows: 1, F6 SuperU; 2, F6 urea + NBPT; 3, F6 UAN; 4, F6 UAN + dual; 5, split UAN; 6, split urea + UAN; 7, F7 SuperU; 8, fall urea; 9, fall SuperU; 10, fall urea + NBPT.

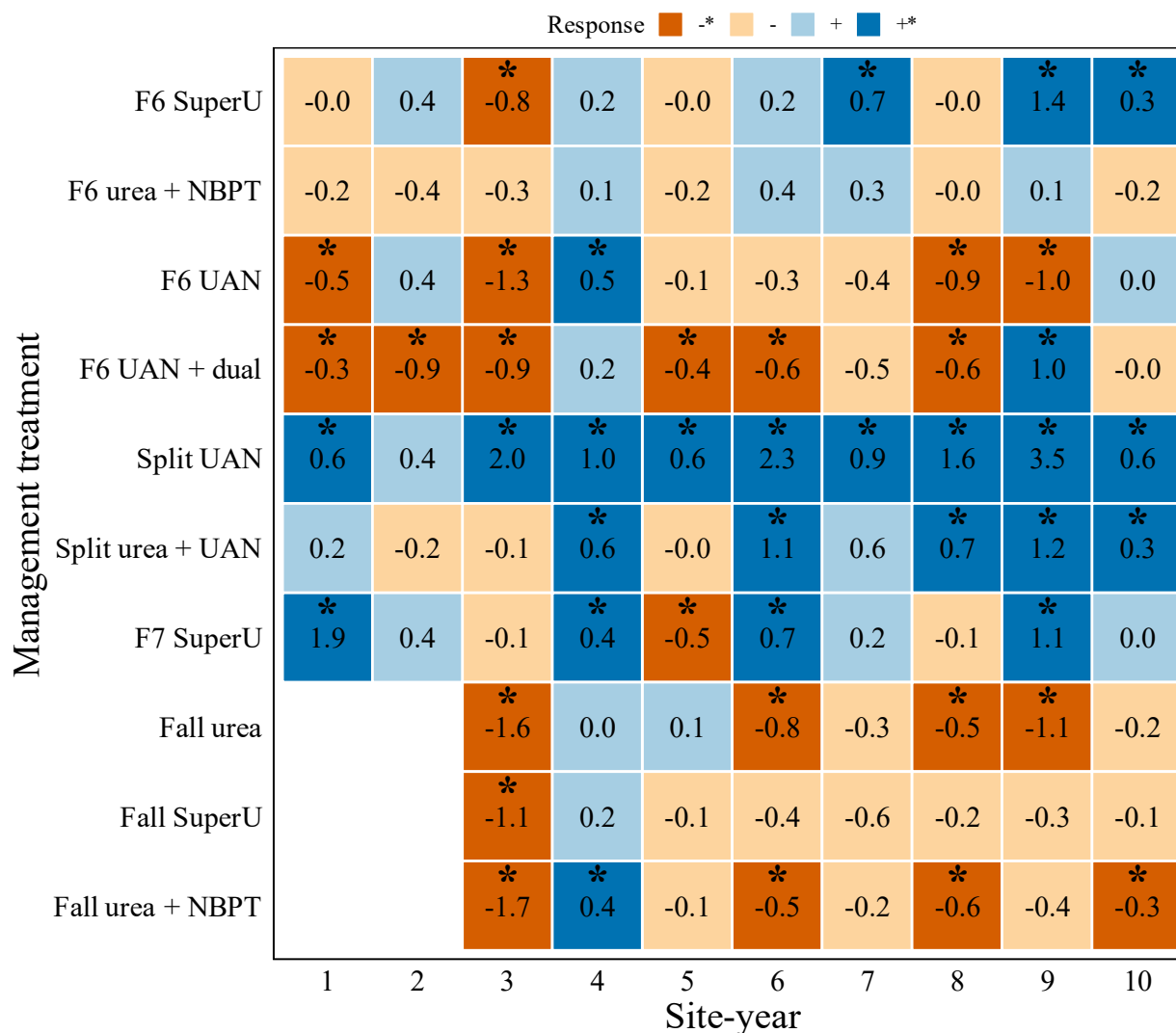


Figure 3.5. Estimated difference in grain protein concentration from the site-specific baseline for management treatments across site-years in Kansas.

Values within each tile are adjusted mean differences from the baseline treatment. Blue tiles indicate positive differences, whereas orange tiles indicate negative differences. Darker shades accompanied by an asterisk (*) indicate differences that are statistically significant from the baseline at the 90% confidence level, whereas lighter shades indicate non-significant differences. F = Feekes growth stage. Management treatments are as follows: 1, F6 SuperU; 2, F6 urea + NBPT; 3, F6 UAN; 4, F6 UAN + dual; 5, split UAN; 6, split urea + UAN; 7, F7 SuperU; 8, fall urea; 9, fall SuperU; 10, fall urea + NBPT.

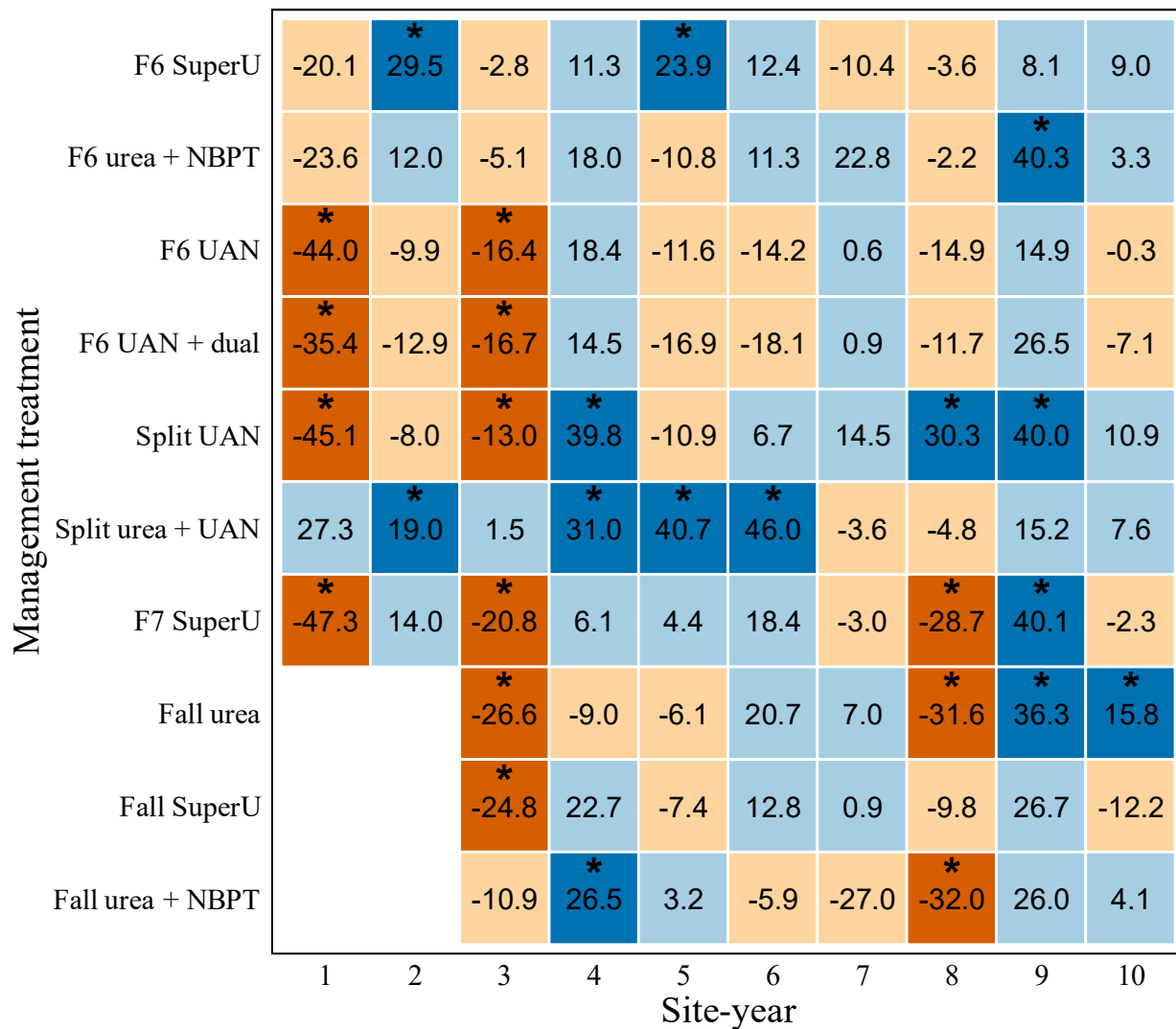


Figure 3.6. Estimated difference in Apparent Recovery Efficiency from the site-specific baseline for management treatments across Kansas site-years.

Values within each tile are adjusted mean differences from the baseline treatment. Blue tiles indicate positive differences, whereas orange tiles indicate negative differences. Darker shades accompanied by an asterisk (*) indicate differences that are statistically significant from the baseline at the 90% confidence level, whereas lighter shades indicate non-significant differences. F = Feekes growth stage. Management treatments are as follows: 1, F6 SuperU; 2, F6 urea + NBPT; 3, F6 UAN; 4, F6 UAN + dual; 5, split UAN; 6, split urea + UAN; 7, F7 SuperU; 8, fall urea; 9, fall SuperU; 10, fall urea + NBPT.

Chapter 4 - General Conclusions

These studies evaluated winter wheat response to N fertilization across diverse Kansas environments by integrating nitrogen (N) rate response and constant rate N management strategies. The objectives were to improve the understanding of how environmental variability influences grain yield, grain protein concentration, and N use efficiency (NUE), and to determine how fertilizer rate and management practices contribute to these responses.

Results demonstrated that crop response to N fertilization varied substantially across site-years. Grain yield varied from highly responsive environments, where yield increased with increasing N rates, to non-responsive environments, where additional N did not result in yield gains. Consequently, the agronomic optimum N rate (AONR) differed widely among environments, reflecting influences from soil N supply, precipitation patterns, and yield potential. In contrast to yield, grain protein concentration responded more consistently to increasing N rates, often continuing to increase even after yield response had plateaued.

Results from the constant N rate management study further demonstrated that alternative fertilizer source, timing, placement, and inhibitor use did not consistently improve grain yield relative to the site-specific expected response. In most environments, yield and agronomic efficiency (AE) responses did not differ significantly among management treatments, indicating that these alternative strategies had limited influence on yield at the constant N rate. However, nitrogen management strategies more frequently influenced grain protein concentration and apparent recovery efficiency (ARE), particularly when the timing of N availability better aligned with crop demand or when environmental conditions increased the risk of N loss.

These findings demonstrate that the effectiveness of nitrogen fertilization in Kansas winter wheat systems is primarily defined by environmental conditions rather than by any single

management practice. Nitrogen rate establishes the overall potential for crop response, while management strategies influence how efficiently that N is utilized and how it is partitioned between yield and grain quality. The lack of consistent treatment effects across site-years indicates that no universal N management strategy can be expected to perform optimally under all conditions. These studies provide an integrated evaluation of N rate and management strategies across diverse environments, providing evidence that both factors should be considered to understand and improve winter wheat productivity and NUE.

These findings highlight the importance of site-specific nitrogen management in Kansas wheat production systems. Producers should account for environmental variability, soil N supply, and their specific production goals when making fertilization decisions, recognizing that N strategies aimed at maximizing grain yield may differ from those intended to improve grain protein concentration or NUE. These results should be interpreted within the context of the environments evaluated, as responses were measured across two growing seasons under rainfed Kansas conditions and constant rate management strategies were assessed at a single N rate. Future research should continue to evaluate nitrogen rate and management strategies across a wider range of environments and growing seasons to improve the understanding of how weather patterns, soil properties, and residual soil N influence winter wheat response to fertilization.