

Improving our ability to manage sorghum stalk rot through fungicide and cropping system
practices in Kansas

by

Leticia Camara Vieira

B. Agr., Federal University of Fronteira Sul, 2022

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Plant Pathology
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2026

Approved by:

Major Professor
Dr. Rodrigo Borba Onofre

Copyright

© Leticia Camara Vieira 2026.

Abstract

Sorghum stalk rot is a worldwide threat to sorghum production and can severely compromise stalk integrity, leading to lodging and yield losses. Unfortunately, there are currently no in-season management options for stalk rots; management recommendations are limited to pre-planting strategies, such as hybrid selection and avoiding excessive planting densities.

The first experiment evaluated the efficacy of fungicide application timing (at planting or flowering) and spray technology (at-planting banded dribbled 5.08 cm off-center below the row (2x2), a dribbled over the row (0x0), or a dribbled 5.08 cm off the row (0x2) placement, and foliar application at the beginning of flowering) for control of stalk rot diseases through on-farm trials. Research trials were established in three farmer fields located in Russell, Dighton, and Bavaria, Kansas during the 2023 and 2024 seasons. Fungicide applications had no significant effect on protein content, panicle size, disease severity, or disease incidence. Both the hybrid and the fungicide application significantly affected grain yield. Overall, applying Xyway™ LFR® at planting by dribbling over the row, and using Topguard® EQ and Adastrio™ at the start of flowering, increased yield compared to the control. Yields were higher with the 0x2 application, where fungicide was dribbled over the row, than with the 0x0 application. Foliar application of fungicide at flowering resulted in a greater yield increase than either planting application alone or combined planting and foliar application. These findings indicate that foliar applications at the flowering stage are the most consistent for maximizing sorghum yield. However, fungicide use did not significantly reduce stalk rot disease in this study.

The second experiment evaluated the influence of different plant densities on sorghum grain yield components, stalk rot severity, and lodging under narrow (38.1 cm) and wide (76.2 cm) row spacing. The plant density observed in this experiment ranged from 59,000 to 160,000 plants ha⁻¹.

Research trials were established in three farmer fields in Russell, Dighton, and Bavaria, Kansas, during the 2024 and 2025 seasons. Sorghum grain yield was consistently higher with wider row spacing across all the locations. Higher yields were observed in Bavaria, followed by Russell and Dighton. Additionally, a positive linear relationship between final stand and sorghum yield was observed. In 2025, stalk rot severity was significantly lower than in 2024. The probability of observing no stalk rot symptoms increased with higher plant density and lower drought stress during flowering, while severity was reduced by higher densities and lower stress during grain filling. Although lodging was observed only in one environment, limiting the assessment of yearly variation, stalk rot severity and wind speed were identified as the primary drivers of occurrence. In cases where lodging occurred, higher plant densities and wider row spacing significantly reduced lodging severity, whereas higher stalk rot severity directly increased the proportion of lodged plants.

Table of Contents

List of Figures	vii
List of Tables	ix
Acknowledgements.....	x
Dedication	xi
Chapter 1 - Introduction.....	1
1.2 Sorghum stalk rot.....	2
1.2.1 Pathogen biology and disease development	3
1.2.2 Effects of environmental stresses on disease development	7
1.3 Disease control.....	8
1.4 Research objectives.....	10
References.....	12
Chapter 2 - Mitigating sorghum stalk rot yield loss through foliar and at-planting fungicide applications	17
2.1 Introduction.....	17
2.2 Materials and methods	19
2.2.1 Field trials	19
2.2.2 Fungicide treatments and application	19
2.2.3 Profitability assessment	20
2.2.4 Data collection	20
2.2.5 Data analysis	21
2.3 Results and Discussion	22
2.3.1 Effect of fungicides on stalk rot.....	22
2.3.2 Pre-harvest lodging	23
2.3.3 Effect of fungicides on yield, protein content, and panicle length	24
2.3.4 Profitability of fungicide applications	26
2.4 Conclusion	26
References.....	28
Tables and Figures	32

Appendix A - Supplementary table.....	39
Chapter 3 - Effects of Plant Density and Row Spacing on Sorghum Stalk Rot and Grain Yield	
Under Environmental Stress	40
3.1 Introduction.....	40
3.2 Materials and methods	43
3.2.1. Experimental site and design	43
3.2.2 Crop measurements and data analysis	44
3.2.3 Data analysis	44
3.3 Results and discussion	46
3.3.1 Grain yield response to management strategies.....	46
3.3.2 Yield components and grain quality	48
3.3.3 Factors influencing stalk rot establishment and severity	49
3.3.4 Interactions of plant density and row spacing on lodging risk and severity	51
3.4 Conclusion	54
References.....	55
Figures	59
Appendix B - Statistical model specifications	65
Appendix C - Regression coefficients table.....	67
Appendix D - Model validation	70

List of Figures

Figure 1.1 Sorghum total production for grain across the major US-producing states (Source: NASS, 2025). Units: 1,000 bushels.	2
Figure 1.2 Characteristic pink-red lesions of Fusarium stalk rot and dark lesions produced by charcoal rot (a). A severely lodged field observed in Dighton, 2024 (b).	6
Figure 2.1 Accumulated weekly precipitation for Bavaria, Dighton, and Russell during the 2024 season. The orange dashed line indicates the timing of the foliar application at flowering. Data extracted from the National Weather Service (NWS) API	37
Figure 2.2 A linear contrast analysis among spray technology and fungicide application timing (at planting or flowering) for sorghum grain yield. Estimates represent the mean differences in yield between specified treatment groups, with dots showing contrast estimates and horizontal lines representing 95% confidence intervals (CI). Contrasts include: (i) at planting 2×2 vs at planting 0×0, (ii) at planting 0×2 vs at planting 0×0, (iii) at planting 2×2 vs. at planting 0×2, (iv) at planting vs. foliar application, and (v) planting + foliar application vs. foliar application.	38
Figure 3.1 Estimated marginal means (95% CI) of sorghum grain yield (kg ha ⁻¹) as influenced under narrow (38.1 cm; 15 in) and wide (76.2 cm; 30 in) row spacing across all site-years.	59
Figure 3.2 Estimated marginal means (95% CI) of panicle size (cm) as influenced under narrow (38.1 cm; 15 in) and wide (76.2 cm; 30 in) row spacing across all site-years.	60
Figure 3.3 Estimated marginal means (95% CI) of grain protein content % as influenced under narrow (38.1 cm; 15 in) and wide (76.2 cm; 30 in) row spacing across all site-years.	61
Figure 3.4 Atmospheric Water Deficit (AWD, mm) during flowering (W1) and grain fill (W2) across three Kansas locations (Bavaria, Dighton, and Russell) during the 2024 and 2025 growing seasons. Positive values indicate an atmospheric water deficit, representing drought stress conditions where evaporative demand exceeded precipitation.	62
Figure 3.5 Regression coefficient estimates for stalk rot severity parameters (ν , μ , σ) in a Zero-Inflated Beta (BEZI) model. Values to the left of the dashed line (negative) indicate a decrease in the parameter, while values to the right (positive) indicate an increase. Error bars represent 95% confidence intervals.	63

Figure 3.6 Regression coefficient estimates for lodging parameters (ν, μ, σ) in a Zero-Inflated Beta (BEZI) model. Values to the left of the dashed line (negative) indicate a decrease in the parameter, while values to the right (positive) indicate an increase. Error bars represent 95% confidence intervals. 64

List of Tables

Table 2.1 Characteristics of field treatments in Bavaria, Russell and Dighton, Kansas, in 2023 and 2024.....	32
Table 2.2 Main effects and interactions for yield, panicle length, protein content, disease severity, incidence, and lodging data for Bavaria, Dighton, and Russell, Kansas.	33
Table 2.3 Effects of environment on sorghum panicle length (cm), protein content (%), yield (kg ha-1), disease incidence and severity (%).	34
Table 2.4 Average grain sorghum yield (kg ha-1) response to fungicide application across locations and years.	35
Table 2.5 Sorghum grain yield average (kg ha-1), marginal net return (\$ ha-1), and profitability of fungicide applications (break-even points (kg ha-1)).	36

Acknowledgements

I would like to express my deepest gratitude to my major advisor, Dr. Rodrigo Borba Onofre, for his mentorship during my Master's at Kansas State University. I am grateful for the opportunities he provided and for his constant investment in my professional growth and the development of my extension skills. I would also like to acknowledge my committee members, Dr. Christopher R. Little, Dr. Erick DeWolf, and Dr. Sarah Sexton-Bowser, for their invaluable support, advice, and suggestions. A special thanks to Dr. Josefina Lacasa and Mr. Claudio Dias da Silva Jr. for their outstanding guidance and expertise in statistical analysis.

I am truly grateful for the collaboration of my lab members, whose hard work with field sampling made this project possible.

My deepest gratitude goes to my husband and family for their unwavering love and encouragement. I will always be thankful for my friends Camila, Eduardo, Claudio, Gabriela, Monalisa, and Ricardo, who became my home away from home. They made this journey lighter, turning the weight of graduate school into something shared and joyful. As an international student, these lifelong bonds are the greatest harvest of my time here.

Finally, I would like to acknowledge the Kansas Sorghum Commission for funding this project.

"O real não está na saída nem na chegada: ele se dispõe para a gente é no meio da travessia." - Guimarães Rosa

Dedication

This work is dedicated to those who, like me, are living proof that education can change lives.

Chapter 1 - Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is part of the grass family Poaceae, and is considered a conventional crop in the semiarid tropics. Sorghum production has been increasing globally, particularly in areas with high population growth driven by its potential as a substitute for common cereals such as corn, rice, and wheat in everyday meals (Aguilar et al., 2023). According to Hamaker et al. (2025), the food industry sector is considered the most promising market for sorghum, and globally around 40% of sorghum production is used for direct human consumption.

Sorghum is considered a key crop for future global food security. Its nutritional properties, such as being gluten-free, immune-modulating properties, and slowly digestible starches, are valuable attributes for human health and have high potential for human food applications as sweeteners, baked goods, and beverages (Stefoska-Needham, 2024; McGinnis & Webster, 2024). In addition to human consumption, sorghum is considered an important source for livestock farming (Zheng et al., 2025). Another reason why sorghum is considered a key crop is its reported ability to tolerate unfavorable climatic conditions and stressful conditions, for example, high temperatures, salinity, drought, and waterlogging (Tari et al., 2013). Sorghum's resilience and its characteristics as a C4 plant, which means that the initial product of carbon fixation in these plants is a 4-carbon molecule, are extremely important, especially considering the recent increase in extreme weather conditions and elevated carbon dioxide (Hariprasanna & Rakshit, 2016; Taiz & Zeiger, 2002).

Grain sorghum production in the USA is centered mainly around the Great Plains region (Assefa et al., 2024). In 2025, Kansas was the top sorghum-producing state with 252 million bushels, followed by Texas with 100.7 million bushels, Colorado with 26 million bushels,

Oklahoma with 23.49 million bushels, and Nebraska with 17.83 million bushels (**Figure 1.1**). The total planted area of sorghum was estimated at 6.64 million acres, with total production estimated at 437 million bushels, an increase of 27% compared to the 2024 total, and an average yield increase of 11.3 bushels per acre (NASS, 2025).

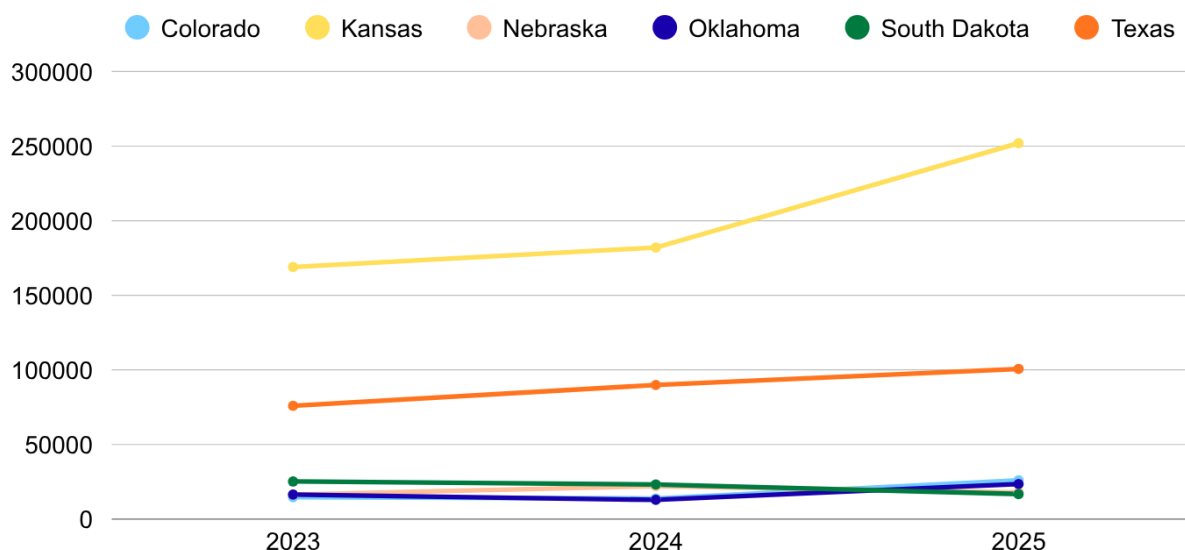


Figure 1.1 Sorghum total production for grain across the major US-producing states (Source: NASS, 2025). Units: 1,000 bushels.

The total area harvested in Kansas in 2024 and 2025 was the same 2.8 million acres; however, the grain production had an increase of 38.46%. This annual yield difference is commonly attributed to environmental conditions, particularly abiotic stress. For example, in 2024, drought stress during flowering and grain filling was observed under field conditions, which is known to trigger a disease complex called “stalk rot”. This disease complex is closely associated with drought stress and high temperatures that can result in significant yield losses.

1.2 Sorghum stalk rot

Stalk rot diseases are among the most important diseases affecting sorghum production across the USA. It's been reported that under stressful conditions, yield losses due to stalk rot and

lodging can reach up to 60% in high-yielding hybrids across Kansas, with annual economic losses exceeding \$15 million (Tesso et al., 2004). The yield reduction is mainly due to the disintegration of vascular tissues, which impacts water and nutrient absorption, and to the complete loss of yield when severe lodging occurs in the field. Specifically, the timing of infection is a critical determinant for yield loss, as pre-flowering infections can reduce seed number and post-flowering infections can decrease seed weight (Bandara et al. 2017a).

Moreover, stalk rot can impact grain quality. For example, in sweet sorghum, stalk rots can negatively affect sugar and sucrose yields, plant height, dried bagasse weight, and °Brix, which are important components for the bioethanol industry (Bandara et al., 2017b; Bandara et al., 2018). In addition, stalk rot diseases can decrease the starch, protein, and fat content of sorghum grain and are negatively correlated with most mineral nutrients (Bandara et al., 2017c).

1.2.1 Pathogen biology and disease development

The predominant stalk rot diseases observed are charcoal rot caused by *Macrophomina phaseolina* (Tassi) Goid and Fusarium stalk rot caused by *Fusarium* spp., including *F. thapsinum* Klittich, J.F. Leslie, P.E. Nelson & Marasas (Little et al., 2018). Both pathogens rely on soil and crop residue for survival. *M. phaseolina* primarily survives as microsclerotia and mycelia in the soil and decaying plant residue. As the residues decay, the sclerotia produced by the fungus are released into the soil, where they can survive for years and germinate in the presence of root exudates (Short et al., 1980; Little et al., 2018). Similarly, *F. thapsinum* survives in crop residue and soil, but mainly as conidia and mycelia, which serve as the primary inoculum (Little et al., 2018). The sexual reproduction of *F. thapsinum* under field conditions is rare because of the strains' low fertility; consequently, the pathogen propagates mainly through an asexual cycle in nature

(Klittich et al., 1997). Furthermore, *F. thapsinum* is considered an endophyte in sorghum, as it can be isolated from healthy plants (Klittich et al., 1997).

Although pathogens associated with the disease are taxonomically distinct, research investigating resistance to stalk rot in grain sorghum has shown that the responses of different genotypes to infection were correlated, regardless of the pathogen causing the infection (Adeyanju et al., 2015). This indicates the presence of broad-spectrum tolerance, suggesting that selecting tolerant hybrids may provide effective management across multiple stalk rot pathogens.

While pathogens are common in the field, the transition from fungal colonization to disease is influenced by several factors. In a study investigating fungal colonization of grain sorghum stalks, it was found that *Fusarium* spp. colonization was lower during the vegetative growth stage and increased during flowering and grain filling (Reed et al., 1983). However, colonization alone was not enough to cause disease in sorghum plants, with stressful conditions and senescence having an important role in favoring the disease development. Specifically, it's known that *M. phaseolina* initially has an endophytic or latent phase, transitioning to a necrotrophic phase by inducing host senescence (Little et al., 2023).

Stalk rot commonly appears during the grain-filling stage, and it's characterized by the deterioration of pith tissue near the base of the stalk, leading to the death of the stalk's pitch cells and potentially plant lodging (Bandara et al., 2017). Charcoal is more common at higher soil temperatures, while *Fusarium* stalk rot is more common at lower temperatures (Claflin & Giorda, 2002). *Macrophomina phaseolina* germinates at high temperatures ranging from 30 to 35 °C and soil moisture below 60%, while the highest average mycelial radial growth of *Fusarium thapsinum* is observed at 25°C, with the minimum growth observed at 15°C (Kaur et al., 2012; Pena et al., 2020). Because the pathogen develops within the stalk, it can colonize the host without showing

apparent external symptoms. Consequently, plants that seem asymptomatic and healthy externally at first look may carry the infection inside (Leslie et al., 1990).

Despite the lack of external symptoms, infected stalks can become fragile and easily crushed under manual pressure, and different internal stalk tissue discolorations can be observed when stalks are split longitudinally, depending on the pathogen (**Figure 1.2**). Fusarium stalk rot can be differentiated from charcoal rot by the lighter pigmentation and slower progression of tissue damage (Zummo, 1984). The massive tissue degradation caused by charcoal rot is explained by the fungus's ability to manipulate sorghum plants to overproduce cell-wall-degrading enzymes (Bandara et al., 2018). When a sorghum plant is infected with charcoal rot, a distinctive dark grey or black pigmentation is observed, and small black sclerotia may appear later in the season as the plant senesces (Little et al., 2018). In contrast, Fusarium stalk rot has reddish, tan-to-pink, or even purple-colored lesions, depending on the plant's genetics, and severe symptoms are often associated with mechanical injury or insect damage (Claflin & Giorda, 2002).

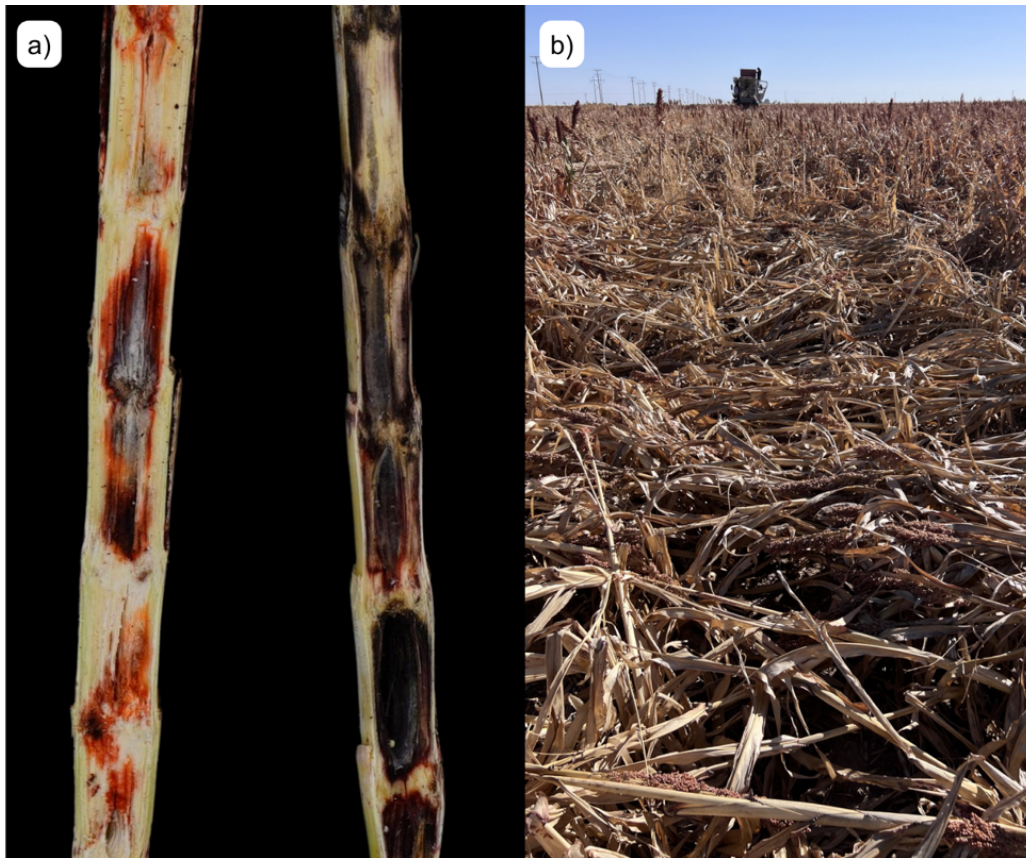


Figure 1.2 Characteristic pink-red lesions of *Fusarium* stalk rot and dark lesions produced by charcoal rot (a). A severely lodged field observed in Dighton, 2024 (b).

Stalk rot symptoms can include reduced panicle size and grain fill, and weakened stalks that cannot support the developing head, resulting in lodged plants in the field (Jardine, 2006; Mughogho & Pande, 1984). Lodging can greatly complicate harvest, resulting in additional yield losses and harvest delays. It's also known that stalk rot affects leaf greenness, reducing leaf chlorophyll content (Bandara et al., 2016). Symptoms can be exacerbated by post-flowering stresses, such as foliar diseases, inadequate fertilization, high plant densities, root rots, or injuries (Pande & Karunakar, 1992).

1.2.2 Effects of environmental stresses on disease development

Environmental conditions have a dominant influence on disease progression. A plant is considered stressed when biotic (living pathogens) or abiotic (non-living environmental conditions) factors negatively affect growth and development (Cooke, 1998). Particularly, for sorghum stalk rot, stressful conditions are closely linked to disease outbreaks in the field. Research findings indicate that the timing of water stress is critical for *M. phaseolina* root colonization in soybeans and sorghum plants, with colonization increasing when irrigation is stopped at the flowering stage (Kendig et al., 2000; Tesso et al., 2010). In addition, drought conditions increase charcoal rot infection and result in smaller sorghum plants and dry weight in greenhouse conditions (Kuri-Aguirre et al., 2025). The reported ability of the *M. phaseolina* to grow at low water potentials suggests that the pathogen is highly adapted and favored in drought conditions (Goudarzi et al., 2008). Similarly, Fusarium stalk rot is intensified by drought and high temperatures, and infection typically occurs when a combination of stressful conditions occurs at flowering, followed by a period of high humidity and cooler temperatures (Little et al., 2018). Under severe moisture stress, the incidence of stalk rot tends to be very high (Seetharama et al., 1987).

Conversely, stressful conditions that favor charcoal rot and Fusarium stalk rot pathogens are considered a dominant constraint on sorghum production, weakening the host plant and increasing the predisposition to infection. Sorghum's response to drought stress includes a reduction of total green leaf area at maturity, and if the stress occurs after anthesis, the translocation of carbohydrates to developing grain may anticipate senescence (Jordan et al., 1984). However, this reduction of total green leaf area caused by drought stress in sorghum plants can be countered by the “stay-green” trait present in some hybrids, by delaying the senescence and maintaining

superior chlorophyll levels, consequently maintaining the photosynthetic machinery capacity over an extended period during the grain filling stage avoiding the translocation of carbohydrates (Abreha et al., 2022; Borrell et al., 2000). Without this stray-green trait, the translocation of carbohydrates from the stalk to the developing grain can cause stalk cells to senesce and die, thereby increasing the plant's susceptibility to infection (Duncan, 1984). Consequently, the stalks become weakened due to the combination of photosynthetic stress and pathogen invasion, and frequently lodge (Mughogho & Pande, 1984). Besides the loss of structural integrity, maximum wind speed is a critical determinant of lodging in sorghum, as it represents the external mechanical forces acting on the plant. When this force exceeds the capacity of the damaged stalk, the plant lodges (Zargar et al., 2021).

1.3 Disease control

Current management recommendations rely mostly on pre-planting strategies. For example, management practices that minimize the crop's exposure to water-deficient conditions and plant stress, such as tillage, weed control, and balanced fertilization, are considered crucial for stalk rot management (Little et al., 2023). Conversely, crop rotation is less effective, especially against *M. phaseolina*, due to its wide host range and high soil persistence (Marquez et al., 2021). Recent studies indicate that excessive planting densities can reduce light transmittance, resulting in lower dry matter accumulation and stalk strength, which consequently increases the risk of stalk lodging (Jin et al., 2023). Likewise, narrow row spacing has also been a strategy adopted to manage the disease, as it can increase radiation absorption by the canopy by improving the plant distribution, better use of resources, and, ultimately, contributing to higher yield (Strieder et al., 2008). However, there is a lack of studies investigating the interaction between plant population

and row spacing on stalk rot development, especially identifying the threshold at which plant density can be increased without negative effects becoming evident under field conditions.

Complementing these agronomic practices, fungicide application is an available management strategy, although it is less often used in low-input crops. Despite in vitro results showing strong inhibitory effects against the pathogens, field results remain inconsistent and are highly dependent on environmental conditions. To illustrate, recent studies indicate that the mycelial growth of *M. phaseolina* can be considerably reduced by the use of fungicides (Mancozeb 75% WP, Carbendazim 50% WP, and Azoxystrobin 11% + Tebuconazole 18.3% SC) under in vitro conditions (Patil et al., 2024). In addition, biological treatments, specifically strains of *Bacillus* species, have also demonstrated efficacy in reducing charcoal rot severity by utilizing multiple mechanisms of antagonism, such as the production of volatile organic compounds under in vitro conditions (Gacitúa A. et al., 2008).

In field conditions, although current fungicides do not have the ability to move downward towards the root system where the pathogen attacks, foliar applications have been employed for stalk rot management due to the stay-green benefit provided by some fungicides, specifically those in the DMI (FRAC group 3) class. Triazoles are known for their potential to significantly improve the plant's ability to withstand abiotic stresses by altering the biosynthesis of phytohormones (Hameed & Farooq, 2021). In a study evaluating the effects of fungicides on sorghum, foliar fungicide applications delayed senescence by 15% to 30%. However, this effect was highly dependent on environmental conditions (Craven et al., 2017). At-planting application of fungicides emerges as a potential strategy to manage stalk rot, especially with triazole-based fungicides, which have high plant mobility and long-lasting effects. For example, when flutriafol (250 g/L SC) was applied as a foliar application at wheat greening stage to determine the final residue levels

in wheat grain and soil, it was demonstrated that flutriafol dissipation was higher than 78% of the initial residue in soil after 45 days (Song et al., 2012).

Host plant resistance is the most efficient method to manage stalk rot diseases. Currently, there is no completely resistant hybrid to *M. phaseolina* in sorghum plants (Marquez et al., 2021). As highlighted by Tesso et al. (2012), developing resistant hybrids is still a challenge due to the presence of multiple pathogens associated with the stalk rot disease complex and the influence of environmental stress on disease development. In addition, hybrid responses to stalk rot can be highly variable. For example, in a study with 300 different sorghum genotypes evaluating the mechanisms behind resistance to *M. phaseolina* and *F. thapsinum*, even though disease severity is correlated under shared environmental stresses, some hybrids showed high resistance, while others showed severe stalk disintegration, highlighting the complexity of the molecular mechanisms underlying resistance (Adeyanju et al., 2015).

1.4 Research objectives

The overarching goal of this study is to improve recommendations for stalk rot disease management for Kansas sorghum producers by evaluating the influence of cropping system and at-planting fungicide applications, ultimately generating and promoting data-driven best management practices.

The specific objectives of the study are to: I) Evaluate the efficacy of fungicide application timing and spray technology for control of stalk rot diseases through on-farm trials. II) Evaluate the influence of agronomic practices on sorghum stalk rot diseases through on-farm trials evaluating row spacing and plant density. Evaluate how the interaction of different row spacings and plant densities influences sorghum grain yield, panicle size, protein content, and stalk rot to

model the probability of lodging occurrence under environmental conditions that induce abiotic stress.

Chapters 2 and 3 provide further elaboration on each objective, with concise descriptions of the chapters and the research goals that drive them. To address Objective 1, Chapter 2 analyzes sorghum yield components and stalk-rot severity data collected from research trials established in three farmer fields in Russell, Dighton, and Bavaria, Kansas, during the 2023 and 2024 seasons. In 2023, trials were established only in Russell, while in 2024 they were conducted in all three locations. To address Objective 2, Chapter 3 analyzes data collected from research trials established in Russell, Dighton, and Bavaria, Kansas, during the 2024 and 2025 seasons.

References

- Abreha, K. B., Enyew, M., Carlsson, A. S., Vetukuri, R. R., Feyissa, T., Motlhaodi, T., Ng'uni, D., & Geleta, M. (2022). Sorghum in dryland: morphological, physiological, and molecular responses of sorghum under drought stress. *Planta*, 255, 20. <https://doi.org/10.1007/s00425-021-03799-7>
- Adeyanju, A., Little, C., Yu, J., & Tesso, T. (2015). Genome-wide association study on resistance to stalk rot diseases in grain sorghum. *G3: Genes, Genomes, Genetics*, 5(6), 1165. <https://doi.org/10.1534/g3.114.016394>
- Aguiar, E. V., Santos, F. G., Queiroz, V. A. V., & Capriles, V. D. (2023). A decade of evidence of sorghum potential in the development of novel food products: Insights from a bibliometric analysis. *Foods*, 12, 3790. <https://doi.org/10.3390/foods12203790>
- Bandara, Y. M. A. Y., Weerasooriya, D. K., Tesso, T. T., Prasad, P. V. V., & Little, C. R. (2017a). Stalk rot fungi affect grain sorghum yield components in an inoculation stage-specific manner. *Crop Protection*, 94, 97-105. <https://doi.org/10.1016/j.cropro.2016.12.018>
- Bandara, Y. M. A. Y., Weerasooriya, D. K., Tesso, T. T., & Little, C. R. (2017b). Stalk rot diseases impact sweet sorghum biofuel traits. *BioEnergy Research*, 10, 26-35. <https://doi.org/10.1007/s12155-016-9775-6>
- Bandara, Y. M. A. Y., Tesso, T. T., Bean, S. R., Dowell, F. E., & Little, C. R. (2017c). Impacts of fungal stalk rot pathogens on the physicochemical properties of sorghum grain. *Plant Disease*, 101(12), 2059–2065. <https://doi.org/10.1094/PDIS-02-17-0238-RE>
- Bandara, Y. M. A. Y., Tesso, T. T., Zhang, K., Wang, D., & Little, C. R. (2018). Charcoal rot and Fusarium stalk rot diseases influence sweet sorghum sugar attributes. *Industrial Crops and Products*, 112, 188-195. <https://doi.org/10.1016/j.indcrop.2017.11.012>
- Bandara, Y. M. A. Y., Weerasooriya, D. K., Liu, S., & Little, C. R. (2018). The Necrotrophic Fungus *Macrophomina phaseolina* Promotes Charcoal Rot Susceptibility in Grain Sorghum Through Induced Host Cell-Wall-Degrading Enzymes. *Phytopathology*, 108, 948-956.
- Borrell, A. K., Hammer, G. L., & Douglas, A. C. L. (2000). Does maintaining green leaf area in sorghum improve yield under drought? I. Leaf growth and senescence. *Crop Science*, 40, 1026–1037.

- Claflin, L. E., & Giorda, L. M. (2002). Stalk rots of sorghum. In J. F. Leslie (Ed.), *Sorghum and millets diseases* (pp. 185–189). Iowa State Press, Ames, Iowa.
- Cooke, B. M. (1998). Disease assessment and yield loss. In D. G. Jones (Ed.), *The Epidemiology of Plant Diseases* (pp. 42-72). Dordrecht: Springer Science+Business Media.
- Craven, M., Smith, K., Berner, J., Morey, L., & McLaren, N. W. (2017). Evaluation of fungicides for potential growth regulating properties on sorghum. *Crop Protection*, 101, 43-49. <http://dx.doi.org/10.1016/j.cropro.2017.07.003>
- Duncan, R. R. (1984). The association of plant senescence with root and stalk diseases in sorghum. In L. K. Mughogho (Ed.), *Sorghum Root and Stalk Rots, a Critical Review* (pp. 99-110). Patancheru, India: ICRISAT.
- Gacitúa, S., Valiente, C., Díaz, K., Hernández, J., Uribe, M., & Sanfuentes, E. (2009). Identification and biological characterization of isolates with activity inhibitive against *Macrophomina phaseolina* (Tassi) Goid. *Chilean Journal of Agricultural Research*, 69(4), 526–533.
- Goudarzi, A., Banihashemi, Z., & Maftoun, M. (2008). Effect of water potential on sclerotial germination and mycelial growth of *Macrophomina phaseolina*. *Phytopathologia Mediterranea*, 47(2), 107–114.
- Hamaker, B. R., Dabat-Partiot, M.-H., vom Brocke, K., Mestres, C., & Taylor, J. R. N. Current and future state of sorghum in the 21st century. In *Sorghum and Millets*. <https://doi.org/10.1016/B978-0-443-23954-0.00019-7>
- Hameed, A., & Farooq, T. (2021). Triazole-based plant growth-regulating agents: A recent update. In *Advances in Triazole Chemistry* (pp. 171–185). Elsevier Inc.
- Hariprasanna, K., & Rakshit, S. (2016). Economic importance of sorghum. In S. Rakshit & Y.-H. Wang (Eds.), *The Sorghum Genome* (pp. 1-25). Springer International Publishing. https://doi.org/10.1007/978-3-319-47789-3_1
- Jardine, D. (2006). Stalk rots of corn and sorghum (Publication No. L-741). Kansas State University Agricultural Experiment Station and Cooperative Extension Service.
- Jin, R., Li, Z., Wang, X., Liu, F., Kong, F., Liu, Q., Lan, T., Feng, D., & Yuan, J. (2023). Optimizing row spacing increases stalk lodging resistance by improving light distribution in dense maize populations. *Agronomy*, 13, 462. <https://doi.org/10.3390/agronomy13020462>

- Jordan, W. R., Clark, R. B., & Seetharama, N. (1984). Role of edaphic factors in disease development. In L. K. Mughogho (Ed.), *Sorghum Root and Stalk Rots, a Critical Review* (pp. 81-98). Patancheru, India: ICRISAT.
- Kendig, S. R., Rupe, J. C., & Scott, H. D. (2000). Effect of irrigation and soil water stress on densities of *Macrophomina phaseolina* in soil and roots of two soybean cultivars. *Plant Disease*, 84, 895-900.
- Klittich, C. J. R., Leslie, J. F., Nelson, P. E., & Marasas, W. F. O. (1997). *Fusarium thapsinum* (*Gibberella thapsina*): A new species in section *Liseola* from sorghum. *Mycologia*, 89(4), 643-652.
- Kuri-Aguirre, K., Leal-Castillo, M., García-Olivares, J. G., & Hernández-Delgado, S. (2025). Effect of biological treatments and water deficit on *Macrophomina phaseolina* infection in sorghum. *Mexican Journal of Phytopathology*, 43(4), 92. <https://doi.org/10.18781/R.MEX.FIT.2024-22>
- Leslie, J. F., Pearson, C. A. S., Nelson, P. E., & Toussoun, T. A. (1990). *Fusarium* spp. from corn, sorghum, and soybean fields in the central and eastern United States. *Phytopathology*, 80(4), 343-350.
- Little, C. R., Bandara, A., Todd, T. C., & Perumal, R. (2018). Sorghum diseases and their management in cultivation: Stalk, root and other diseases. In D. L. Sparks (Ed.), *Achieving sustainable cultivation of sorghum: Volume 1*. Burleigh Dodds Science Publishing. <https://doi.org/10.19103/AS.2017.0015.31>
- Little, C. R., Perumal, R., Tesso, T., Bandara, Y. M. A. Y., & Noor, A. (2023). Chapter 4: Charcoal rot: a major root and stalk disease of sorghum. In *Macrophomina Phaseolina*. <https://doi.org/10.1016/B978-0-443-15443-0.00018-8>
- Marquez, N., Giachero, M. L., Declerck, S., & Ducasse, D. A. (2021). *Macrophomina phaseolina*: General characteristics of pathogenicity and methods of control. *Frontiers in Plant Science*, 12, 634397. <https://doi.org/10.3389/fpls.2021.634397>
- McGinnis, M. J., & Webster, M. (2024). Current and potential future uses of sorghum to increase nutrient density for human foods. *Journal of Food Science*, 89, A42–A51. <https://doi.org/10.1111/1750-3841.17571>
- Mughogho, L. K., & Pande, S. (1984). Charcoal rot of sorghum. In L. K. Mughogho (Ed.), *Sorghum Root and Stalk Rots, a Critical Review* (pp. 11-24). Patancheru, India: ICRISAT.

- National Agricultural Statistics Service. (2026). Crop production 2025 summary (ISSN: 1057-7823). U.S. Department of Agriculture.
- Patil, N. H., Magar, S. J., Ardad, S. S., Waghmare, N. N., and Patil, S. U. (2024). In vitro evaluation of fungicides against *Macrophomina phaseolina* associated with charcoal rot of maize. Int. J. Adv. Biochem. Res. 8(S10):1492-1494.
- Pande, S., & Karunakar, R. I. (1992). Stalk rots. In W. A. J. de Milliano, R. A. Frederiksen, & G. D. Bengston (Eds.), Sorghum and millets diseases: A second world review (pp. 219–234). International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, India.
- Pena, G. A., Sulyok, M., & Chulze, S. N. (2020). Effect of interacting conditions of water activity, temperature and incubation time on *Fusarium thapsinum* and *Fusarium andiyazi* growth and toxin production on sorghum grains. International Journal of Food Microbiology, 318, Article 108468. <https://doi.org/10.1016/j.ijfoodmicro.2019.108468>
- Reed, J. E., Partridge, J. E., and Nordquist, P. T. (1983). Fungal colonization of stalks and roots of grain sorghum during the growing season. Plant Disease 67:417-420.
- Seetharama, N., Bidinger, F. R., Rao, K. N., Gill, K. S., & Mulgund, M. (1987). Effect of pattern and severity of moisture deficit stress on stalk rot incidence in sorghum. Field Crops Research, 15(3-4), 289–308.
- Short, G. E., T. D. Wyllie, and P. R. Bristow. (1980). Survival of *Macrophomina phaseolina* in soil and in residue of soybean. Phytopathology 70:13-17.
- Song, Y., Zou, Z., Gong, Y., Shan, W., Li, W., and Han, L. (2012). Dissipation and residues of flutriafol in wheat and soil under field conditions. Bull. Environ. Contam. Toxicol. 89:611-614. <https://doi.org/10.1007/s00128-012-0749-x>
- Stefoska-Needham, A. (2024). Sorghum and health: an overview of potential protective health effects. Journal of Food Science, 89, A30–A41. <https://doi.org/10.1111/1750-3841.16978>
- Strieder, M. L., Silva, P. R. F., Rambo, L., Sangoi, L., Silva, A. A., Endrigo, P. C., & Jandrey, D. B. (2008). Crop management systems and maize grain yield under narrow row spacing. Scientia Agricola, 65(4), 346–353. <https://doi.org/10.1590/S0103-90162008000400004>
- Surinder Kaur, Gurpreet Singh Dhillon, Satinder Kaur Brar, Gary Edward Vallad, Ramesh Chand & Vijay Bahadur Chauhan (2012) Emerging phytopathogen *Macrophomina phaseolina*:

- biology, economic importance and current diagnostic trends, *Critical Reviews in Microbiology*, 38:2, 136-151, DOI: 10.3109/1040841X.2011.640977
- Tari, I., Laskay, G., Takács, Z., and Poór, P. (2013). Response of sorghum to abiotic stresses: A review. *J. Agron. Crop Sci.* 199:264-274. <https://doi.org/10.1111/jac.12017>
- Taiz, L., & Zeiger, E. (2002). *Plant physiology* (3rd ed.). Sunderland: Sinauer Associates
- Tesso, T. T., Ochanda, N., Little, C. R., Claflin, L., & Tuinstra, M. R. (2010). Analysis of host plant resistance to multiple *Fusarium* species associated with stalk rot disease in sorghum. *Field Crops Research*, 118, 177–182. <https://doi.org/10.1016/j.fcr.2010.05.010>
- Zargar, O., Li, Q., Nwaobi, C., Pharr, M., Finlayson, S. A., & Muliana, A. (2021). Thigmostimulation alters anatomical and biomechanical properties of bioenergy sorghum stems. SSRN. <https://doi.org/10.2139/ssrn.3957953>
- Zheng, M., Tutar, H., Shaghaleh, H., Hamoud, Y. A., Er, H., Omac, B., Yildirim, G., Eren, Ö., Khalifa, M., & Mwamahonje, A. (2025). Assessing the impact of climate change on the sustainability of sorghum production: A bibliometric analysis. *Sustainable Development*. <https://doi.org/10.1002/sd.70397>
- Zummo, N. (1984). *Fusarium Root and Stalk Disease Complex. Sorghum Root and Stalk Rots, a Critical Review* (pp. 25-30). Bellagio, Italy. Patancheru, India: ICRISAT.

Chapter 2 - Mitigating sorghum stalk rot yield loss through foliar and at-planting fungicide applications

* A modified version of this chapter has been published by the Plant Health Progress Journal.

Citation: Vieira, L. C., Dinkel, C., Wisbey, J., Little, C. R., Andersen Onofre, K., & Onofre, R. B. (2026). Mitigating sorghum stalk rot yield loss through foliar and at-planting fungicide applications. Plant Health Progress. <https://doi.org/10.1094/PHP-11-25-0267-RS>

2.1 Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is considered a resilient crop, with reported ability to tolerate unfavorable climatic conditions and stressful conditions such as high temperatures, salinity, drought, and waterlogging (Tari et al., 2013). In 2024, an estimated 6.30 million acres were planted in the United States with production estimated at 344 million bushels, representing an increase of 8% compared to the total planted area in 2023 (USDA NASS, 2025). Despite its resilience, sorghum productivity can be significantly reduced by the presence of stalk rots, which can lead to yield losses up to 50% under high disease pressure (Tesso et al., 2004).

Stalk rots are among the most important diseases affecting sorghum production across the United States. The predominant stalk rot diseases observed are charcoal rot caused by *Macrophomina phaseolina* (Tassi) Goid. and Fusarium stalk rot caused by *Fusarium* spp., including *F. thapsinum* Klittich, J.F. Leslie, P.E. Nelson & Marasas (Little et al., 2018). According to Bandara et al. (2017), the first symptoms of stalk rot commonly appear during the grain-filling stage with the degradation of pith tissue or tissue near the stalk's base, resulting in internal stalk damage. As a result, the integrity of the stalk is greatly reduced. Stalk rots can reduce yields by

reducing panicle size, decreasing grain fill, and weakening stalks until they cannot hold up the developing head, resulting in lodged plants in the field (Jardine, 2006; Mughogho & Pande, 1984). Lodging can greatly complicate harvest, resulting in additional yield losses and delayed harvest.

Furthermore, stalk rots can be made worse by any stress that reduces photosynthate production, particularly post-flowering, which leads to the remobilization of carbohydrates from the stalks. In particular, Pande and Karunakar (1992) found that stress and damage contribute to disease development in sorghum, such as the presence of foliar diseases, high planting density, drought, hail damage, unbalanced fertilization (specifically low K with high N), the presence of root rots, and injury from root and stalk insects. Host plant resistance would be the most efficient method to manage stalk rot diseases. However, as highlighted by Tesso et al. (2012), developing resistant hybrids is still a challenge due to the presence of multiple pathogens associated with the stalk rot disease complex and the influence of environmental stress on disease development.

Fungicides recommended for grain sorghum are effective in controlling a broad range of diseases, including anthracnose, ergot, rust, and various leaf spots. Commonly used products include in FRAC Mode of Action (MOA) Group 11 (azoxystrobin and pyraclostrobin), and MOA Group 3 (flutriafol and propiconazole), as well as premixes that combine multiple modes of action to provide broader disease protection (Martinez Espinoza, 2025). Recent studies indicate that the mycelial growth of *M. phaseolina* can be reduced using fungicides (Mancozeb 75% WP, Carbendazim 50% WP, and Azoxystrobin 11% + Tebuconazole 18.3% SC) under in vitro conditions (Patil et al., 2024). However, the effectiveness of fungicide application under field conditions for reducing stalk rot severity in sorghum has not been studied, especially under conditions where susceptible crops are grown continuously, increasing the risk of recurrent outbreaks of the disease due to the pathogen's survival in crop residue and soil.

Therefore, the objective of this study was to evaluate the efficacy of fungicide applications for controlling stalk rot diseases through on-farm trials.

2.2 Materials and methods

2.2.1 Field trials

Research trials were established in three farmer fields located in Russell, Dighton, and Bavaria, Kansas during the 2023 and 2024 seasons. In 2023, trials were established only in Russell, while in 2024 they were conducted in all three locations. These sites were selected based on grower reports of historically high stalk rot pressure and recurring lodging outbreaks. A continuous grain sorghum cropping system was used at all locations. Trials were conducted using standard management practices for each region. Pioneer® hybrids 85P44 and 84P72, both susceptible to stalk rot disease, were planted using a 4-row SRES small-plot research planter (Kincaid Equipment Manufacturing). Seeding rates varied by location: 79,058 seeds ha⁻¹ in Dighton, 111,163 seeds ha⁻¹ in Russell, and 135,890 seeds ha⁻¹ in Bavaria. Experimental plots were 3.04 m wide (4 rows/plot with 76.2 cm between each row) and 7.72 m long with alleys of 1.52 m width separating the plot ends. No artificial inoculation was performed.

2.2.2 Fungicide treatments and application

The experiment was arranged as a randomized complete block design with six replications per treatment. A factorial arrangement was used, with hybrid (two levels) and fungicide treatment (seven levels), including a non-treated control and six unique combinations of fungicides and application methods. At-planting fungicides were applied using a SRES small-plot research planter (Kincaid Equipment Manufacturing) pressurized at 30 PSI and delivering 84.15 L ha⁻¹ of water volume. At growth stage 6, when around 50% of the plants in the field blooming (Ciampitti &

Carcedo, 2023), treatments were applied using a CO₂-powered backpack sprayer at a pressure of 30 PSI and calibrated to deliver 187 L ha⁻¹ water volume. At-planting, Xyway™ LFR® (flutriafol; FMC Corporation, FRAC Group 3) was applied using three different technologies: banded dribbled 5.1 cm off-center below the row (2x2), dribbled over the row (0x0), or dribbled 5.1 cm off the row (0x2). At growth stage 6 (flowering), Topguard® EQ (flutriafol + azoxystrobin, FMC Corporation, FRAC groups 3 and 11), and Adastrio™ (azoxystrobin + Fluindapyr + flutriafol, FMC Corporation, FRAC groups 11, 7, and 3) were applied as foliar sprays. A combination treatment of Xyway™ LFR® with banded at planting (2x2), followed by Topguard EQ at flowering, was also included. Treatment descriptions are presented in **Table 2.1**.

2.2.3 Profitability assessment

The profitability of fungicide application was estimated in U.S. dollars (USD) based on average prices reported by local retailers in Kansas in 2024 for Xyway™ LFR® (\$49.42 ha⁻¹), Topguard® EQ (\$37.07 ha⁻¹), and Adastrio™ (\$49.42 ha⁻¹). The estimated cost (labor + diesel + repair + operator + machinery depreciation) for ground fungicide application was \$28.01 ha⁻¹ (Ibendahl et al., 2015). No application cost was considered for at-planting fungicide treatments, since these products were applied during the planting operation. The average grain sorghum price in 2024 was \$0.1905 kg⁻¹ (\$190.5 t⁻¹) (USDA NASS, 2024). The break-even yield point was calculated based on: [(fungicide cost + application cost)/grain sorghum price] for each fungicide treatment (Faske et al., 2021).

2.2.4 Data collection

Ten plants were randomly selected from the first and fourth rows of each plot prior to harvest for stalk rot severity evaluation. Stalks from the collected plants were split, and the bottom

25.4 cm (10 in) were photographed. Severity measurements were taken using the Pliman package in R (Monteiro, 2023), which allows separating healthy and diseased tissue based on color differences and calculates the percentage of symptomatic area for each image. Incidence was visually assessed on the same stalks based on the presence of stalk rot symptoms. The panicle length of the same 10 plants was measured using a ruler from where the panicle starts on the peduncle to the tip of the panicle. Grain yield was determined by harvesting the 2nd and 3rd rows of each plot using a self-propelled small plot combine (Kincaid 8XP, Haven, KS). Yield calculations were adjusted for moisture content at 15%

2.2.5 Data analysis

The normal distribution and homogeneity of variances for the data were verified using Proc Univariate in SAS software version 9.2. For the 2023 season, only yield data were included in the analysis. Data were analyzed using a Linear Mixed-Effects model (PROC MIXED). Locations were analyzed in a combined model that assumed common residual variance across locations, allowing treatment effects to be estimated within each location while testing whether treatment responses differ among locations. The model incorporated hybrid, treatment, and location as fixed effects, including all two-way and three-way interactions (treatment × hybrid × location). Block was treated as a random effect (block(hybrid × location)). Least squares means were compared using Tukey's adjustment for main effects, and interaction was investigated by slicing the effect. Linear contrasts were used to compare the efficacy of spray technology and the timing of fungicide application, either at planting or at flowering.

2.3 Results and Discussion

2.3.1 Effect of fungicides on stalk rot

During the 2024 season, stalk rots were present in all locations and across all trials. Significant main effects of location were detected for both severity ($p < 0.0001$) and incidence ($p < 0.0001$), suggesting that disease development differed between locations (**Table 2.2**). Tukey-adjusted post-hoc comparisons indicated that Russell had lower severity (50.55%) compared to both Bavaria (61.52%) and Dighton (62.60%). In contrast, a higher incidence was observed in Bavaria (86.78%) compared to both Dighton (49.97%) and Russell (76.07%). However, fungicide applications at planting or at flowering did not significantly reduce stalk rot severity ($p = 0.1241$) or incidence ($p = 0.7823$). No significant interactions were observed.

Silva et al. (2021) highlight that flutriafol is a DMI-fungicide (FRAC group 3) and is considered a triazole that has the characteristic of high plant mobility. According to Toda et al. (2021), triazoles are among the most used fungicides in agriculture, with sales data estimating they represent more than 25% of worldwide fungicide sales. Previous work has reported that an application of azoxystrobin and flutriafol at flowering in grain sorghum may result in yield improvement under highly conducive weather for disease development (Fromme et al., 2017). Additionally, in vitro studies evaluating the efficacy of systemic fungicides have shown 100% inhibition of *Macrophomina phaseolina* (Archana et al., 2022). Likewise, in corn, foliar fungicide applied at silking was able to reduce lodging by 9.3% while also leading to yield improvements (Robertson et al., 2020). However, our study showed no significant effect of treatments on stalk rot development. We suggest that, given the biology of stalk rot pathogens, which colonize the internal stalk tissues (primarily the pith) and are frequently triggered by plant stress, fungicide efficacy may be limited under favorable conditions for disease development and high disease

pressure. Another aspect to consider is the timing of infection. It is possible that stalk rot infection occurs later in the season, when fungicide residual may be reduced to levels that are ineffective for disease suppression. Flutriafol persistence in plant tissues can differ depending on the plant species (Zhang et al., 2015). For example, when flutriafol (250 g/L SC) was applied as a foliar application at wheat greening stage to determine the final residue levels in wheat grain and soil, it was demonstrated that flutriafol dissipation was higher than 78% of the initial residue in soil after 45 days (Song et al., 2012).

2.3.2 Pre-harvest lodging

Pre-harvest lodging was only observed at Dighton (>30%) (**Table 2.3**). However, like stalk rot severity, fungicide applications did not reduce lodging severity ($p = 0.7907$). There are both physiological and environmental interactions that contribute to stalk rot, making it a complex issue. Drought stress during grain filling is a key factor initiating processes that result in charcoal rot disease and plant lodging in sorghum (Mughogho and Pande 1984). Similarly, a study to evaluate the effect of drought stress on charcoal rot development in soybeans suggests that late-season drought stress may be a bigger driver for disease development than drought stress earlier during the season (Zaccaron et al., 2024). As seen in May and mid-July of 2024 in this experiment, during early vegetative growth, all locations had adequate moisture. However, during flowering and grain fill (August to September), Dighton received lower precipitation (26.0 mm [1.02 in]) compared to Bavaria (50.2 mm [1.98 in]) and Russell (49.3 mm [1.94 in]), which may have led to post-flowering stress impacting yield and disease development (**Figure 2.1**). This underscores how environmental factors may significantly impact stalk rot development, since they infect and cause disease under favorable conditions that lead to increased host susceptibility (Tesso et al. 2012; Dodd, 1980). In addition, it's known in corn that abiotic stresses such as heavy storms, drought,

foliar diseases, or herbicide damage can reduce the plant's ability to photosynthesize and produce carbohydrates, and as a result, the plant relies more on stored carbohydrates from the stalks, which can increase lodging severity (Nielsen & Colville, n.d.). Therefore, the interaction between the environment and the host plays a crucial role in determining the development and outbreaks of stalk rot in a field (Dodd, 1980).

2.3.3 Effect of fungicides on yield, protein content, and panicle length

Across all locations, significant main effects for sorghum grain yield were observed for hybrid ($p = 0.0563$), location ($p < 0.0001$), and fungicide application ($p = 0.0003$) (**Table 2.2**). Fungicide treatments, particularly Xyway™ LFR® applied at planting 0×0 (T3), Topguard® EQ (T6), and Adastrio™ (T7) at early flowering, resulted in yield increases of 464.98, 484.53, and 505.00 kg ha⁻¹, respectively, compared to the control. A significant interaction between fungicide application location ($p = 0.0209$) was observed; however, this interaction reflected differences in effect size, suggesting that the magnitude of the yield response varied across locations rather than the direction of the response, as all locations showed a positive yield response. These findings are consistent with previous research, which indicates that yield response to fungicide treatments can be highly variable between different locations (Smitha et al., 2015).

Additionally, greater yields for Pioneer hybrid 84P72, which outperformed Pioneer hybrid 85P44 by +379.81 kg ha⁻¹, representing a 7.76% yield increase. Higher yields were observed for Russell during the 2024 season (5996.94 kg ha⁻¹) and 2023 season (5618.11 kg ha⁻¹), followed by Bavaria (4313.12 kg ha⁻¹) and Dighton (2819.32 kg ha⁻¹), while no significant year-to-year differences were detected for Russell ($p = 0.5675$) (**Table 2.3**).

To evaluate the efficacy of spray technology and the timing of fungicide application, either at planting or at flowering, a linear contrast analysis was used to compare specific treatment groups

(**Figure 2.2**). A yield difference was observed between the 0×0 and 0×2 applications, with dribbling over the top of the row (0×0) producing higher yields ($p = 0.0053$). No yield differences were observed between 2×2 vs 0×0 or 2×2 vs 0×2 groups. Foliar application resulted in a significant yield increase compared to both at planting-only applications ($p = 0.0110$) and combined planting and foliar applications ($p = 0.0011$). Similar results have been reported for other systemic fungicides, such as propiconazole and hexaconazole, applied after flowering in sorghum, resulting in improved grain yields (Desai et al., 2021). In contrast, for corn, a meta-analysis reported that at-planting flutriafol applications (banded 2×2 or 2×0) led to a yield increase and reduced foliar disease severity when conditions were conducive to disease development (Silva, 2024).

In water-limited environments, higher yields have also been observed when fungicide applications have been included as part of a high-input management strategy (McHenry et al., 2016). The yield increase observed by fungicide application, especially triazoles, is likely related to plant growth-regulating properties, delayed senescence, reduced seed quality losses, and controlling sorghum grain mold (Craven et al., 2017; Hepperly et al., 1987).

For panicle length, significant main effects of location ($p < 0.0001$), and a hybrid × location interaction ($p = 0.0032$) were observed as shown in **Table 2.2**. No significant effect was observed for fungicide application. Similarly, results for protein content suggest a significant effect of location ($p < 0.0001$), while fungicide application had no effect. As expected, lower protein content was observed for Russell (7.87%), followed by Bavaria (10.92%) and Dighton (11.85%), since as yield increases, protein concentration tends to decrease (Ross et al., 1981).

2.3.4 Profitability of fungicide applications

Based on break-even points calculated using local input costs for fungicide applications, the minimum yield increases required for profitability were estimated at 259.4 kg ha⁻¹ for Xyway™ LFR®, 341.62 kg ha⁻¹ for Topguard® EQ, and 406.45 kg ha⁻¹ for Adastrio™. Under the conditions of this study, only Xyway LFR™ LFR®, applied at planting by dribbling over the top of the row (0×0 placement), and Topguard® EQ and Adastrio™ applied as a foliar spray at flowering were profitable resulting in 465.43 kg ha⁻¹, 484.74 kg ha⁻¹, and 505.20 kg ha⁻¹, respectively, higher than the non-treated control (**Table 2.5**). In addition, the marginal return for Xyway™ LFR®, applied at planting by dribbling over the top of the row (0×0 placement), and Topguard® EQ and Adastrio™ applied as a foliar spray at flowering were 883.8 \$ ha⁻¹, 879.0 \$ ha⁻¹, and 870.5 \$ ha⁻¹, respectively, which was higher than the non-treated control (844.3 \$ ha⁻¹) (**Table 2.5**).

2.4 Conclusion

Overall, at-planting and foliar fungicide applications did not reduce stalk rot severity and incidence. Although the magnitude of the yield responses to fungicide application varied across environments, fungicide application consistently increased sorghum yield across locations. A significant difference in yield was observed between the 0×0 and 0×2 applications, with dribbling over the top of the row resulting in higher yields ($p = 0.005$). Foliar applications resulted in a significant yield increase compared to both at planting-only applications ($p = 0.011$) and combined planting and foliar applications ($p = 0.001$). Additionally, this study emphasizes the need to understand the timing of pathogen infection and disease progression in sorghum stalk rots, as well as to examine other management approaches for controlling stalk rot diseases, such as seed

treatments and cropping systems. Future work should aim to better understand what is driving the yield benefits observed in this study.

References

- Archana, B. M., Govindappa, M. R., Yenjerappa, S. T., Aswathanarayana, D. S., and Girish, G. 2022. Bioefficacy of bioagents and fungicides against *Macrophomina phaseolina* (Tassi) Goid. causing charcoal rot disease in sorghum crop. *Environ. Ecol.* 40(3A):1223-1228.
- Bandara, Y. M. A. Y., Weerasooriya, D. K., Tesso, T. T., Prasad, P. V. V., and Little, C. R. 2017. Impacts of fungal stalk rot pathogens on physicochemical properties of sorghum grain. *Plant Dis.* 101:2059-2065. <https://doi.org/10.1094/PDIS-02-17-0238-RE>.
- Ciampitti, I.A., and Carcedo, A.P. 2023. Sorghum growth and development (MF3234). Kansas State University Agricultural Experiment Station and Cooperative Extension Service.
- Craven, M., Smith, K., Berner, J., Morey, L., and McLaren, N. W. 2017. Evaluation of fungicides for potential growth regulating properties on sorghum. *Crop Prot.* 101:43-49. <https://doi.org/10.1016/j.cropro.2017.07.003>.
- Desai, V. K., Rakholiya, K. B., and Patil, V. A. 2021. Efficacy of fungicides on grain mold of sorghum. *Int. J. Curr. Microbiol. App. Sci.* 10:648-652.
- Dodd, J. 1980. The role of plant stresses in development of corn stalk rots. *Plant Dis.* 64:533-537.
- Faske, T. R., Kelley, J., and Spurlock, T. 2021. Effect of fungicides and hybrids on foliar diseases of grain sorghum in Arkansas. *Crop Prot.* 149:105767. <https://doi.org/10.1016/j.cropro.2021.105767>.
- Fromme, D. D., Price, T., Lofton, J., Isakeit, T., Schnell, R., Dodla, S., Stephenson, D., Grichar, W. J., and Shannon, K. 2017. Effect of fungicide applications on grain sorghum (*Sorghum bicolor* L.) growth and yield. *Int. J. Agron.* 2017: Article ID 5927816. <https://doi.org/10.1155/2017/5927816>.
- Hepperly, P. R., Feliciano, C., and Sotomayor-Rios, A. 1987. Influence of panicle fungicides and harvest schedules on sorghum seed quality under humid tropical conditions in Puerto Rico. *J. Agric. Univ. P. R.* 71(1):76-83.
- Hameed, A., and Farooq, T. 2021. Triazole-based plant growth-regulating agents: A recent update. In: *Advances in Plant Physiology*, pp. 169-185. Elsevier. <https://doi.org/10.1016/B978-0-12-817113-4.00008-1>.
- Ibendahl, G., O'Brien, D.M., and Shoup, D. (2015). Grain sorghum cost–return budget in Southeast Kansas (MF995). Kansas State University Agricultural Experiment Station and Cooperative Extension Service.

- Jardine, D. (2006). Stalk rots of corn and sorghum (Publication No. L-741). Kansas State University Agricultural Experiment Station and Cooperative Extension Service.
- Little, C.R., Perumal, R., Bandara, Y.M.A.Y., and Todd, T.C. 2018. Sorghum diseases and their management in cultivation: stalk, root and other diseases. In: Achieving Sustainable Cultivation of Sorghum, Vol. 1. Burleigh Dodds Science Publishing. <https://doi.org/10.19103/AS.2017.0015.31>.
- Little, C.R., Perumal, R., Tesso, T., Bandara, Y.M.A.Y., and Noor, A. 2023. Charcoal rot: A major root and stalk disease of sorghum. In: *Macrophomina phaseolina*: Ecobiology, Pathology and Management, pp. 33-54. Elsevier. <https://doi.org/10.1016/B978-0-443-15443-0.00018-8>.
- McHenry, B., Adey, E., Kimball, J., Prasad, P. V. V., and Ciampitti, I. A. 2016. Balanced nutrition and crop production practices for closing sorghum yield gaps. Kans. Agric. Exp. Stn. Res. Rep. 2(5). <https://doi.org/10.4148/2378-5977.1219>.
- Martinez Espinoza, A. 2025. Sorghum disease control. In University of Georgia Cooperative Extension, 2025 Georgia pest management handbook: Commercial edition (Vol. 1) (Special Bulletin 28). <https://extension.uga.edu>.
- Monteiro, L. 2023. Pliman: Plant image analysis. R package version 1.0.2. <https://CRAN.R-project.org/package=pliman>.
- Mughogho, L.K., and Pande, S. 1984. Charcoal rot of sorghum. In: Sorghum Root and Stalk Rots: A Critical Review, pp. 11-20. Proc. Consult. Group Disc. Res. Needs Strateg. Control Sorghum Root Stalk Rot Dis., 27 Nov.-2 Dec. 1983, Bellagio, Italy. Patancheru, A.P., India: ICRISAT.
- Nielsen, R. L., and Colville, D. n.d. Stalk lodging in corn: Guidelines for preventive management (AY-262). Purdue University Cooperative Extension Service. <https://www.extension.purdue.edu/extmedia/ay/ay-262.html>.
- Pande, S., and Karunakar, R. I. 1992. Stalk rots. ICRISAT, Patancheru, India.
- Patil, N.H., Magar, S.J., Ardad, S.S., Waghmare, N.N., and Patil, S.U. 2024. In vitro evaluation of fungicides against *Macrophomina phaseolina* associated with charcoal rot of maize. Int. J. Adv. Biochem. Res. 8(S10):1492-1494.
- Robertson, A. E., Serrano, M., Acharya, J., Shriver, J., Beckman, J., Huffman, C., Pecinovsky, K., Rees, M., Schaben, D., Schnabel, M., Sievers, J., and Tuttle, T. 2020. Effect of foliar

- fungicides applied at silking on stalk lodging in corn. *Plant Health Prog.* 21:2-8. <https://doi.org/10.1094/PHP-08-19-0049-RS>.
- Ross, W. M., Kofoed, K. D., Maranville, J. W., and Voigt, R. L. 1981. Selecting for grain protein and yield in sorghum random-mating populations. *Crop Sci.* 21(5):775-779. <https://doi.org/10.2135/cropsci1981.0011183X002100050036x>.
- Silva, M. B. 2024. Assessment of corn yield and physiological performance via fungicide placement and intensive management strategies. M.S. thesis. Purdue Univ. Grad. Sch. <https://doi.org/10.25394/PGS.26409499.v1>.
- Silva, T. S., Fonseca, L. F. da, Yamada, J. K., and Pontes, N. de C. 2021. Flutriafol and azoxystrobin: An efficient combination to control fungal leaf diseases in corn crops. *Crop Prot.* 140:105394. <https://doi.org/10.1016/j.cropro.2020.105394>.
- Smitha, K., Craven, M., McLaren, N. W., and Berner, J. M. 2015. Effects on fungicide application on sorghum yield, leaf senescence and photosynthetic efficiency in South Africa. *S. Afr. J. Bot.* 98:201. <https://doi.org/10.1016/j.sajb.2015.03.121>.
- Song, Y., Zou, Z., Gong, Y., Shan, W., Li, W., and Han, L. 2012. Dissipation and residues of flutriafol in wheat and soil under field conditions. *Bull. Environ. Contam. Toxicol.* 89:611-614. <https://doi.org/10.1007/s00128-012-0749-x>.
- Surinder Kaur, Gurpreet Singh Dhillon, Satinder Kaur Brar, Gary Edward Vallad, Ramesh Chand & Vijay Bahadur Chauhan (2012) Emerging phytopathogen *Macrophomina phaseolina*: biology, economic importance and current diagnostic trends, *Critical Reviews in Microbiology*, 38:2, 136-151, DOI: 10.3109/1040841X.2011.640977
- Tari, I., Laskay, G., Takács, Z., and Poór, P. 2013. Response of sorghum to abiotic stresses: A review. *J. Agron. Crop Sci.* 199:264-274. <https://doi.org/10.1111/jac.12017>.
- Tesso, T., Claflin, L.E., and Tuinstra, M.R. 2004. Estimation of combining ability for resistance to *Fusarium* stalk rot in grain sorghum. *Crop Sci.* 44(4):1195-1199. <https://doi.org/10.2135/cropsci2004.1195>.
- Tesso, T., Perumal, R., Little, C.R., Adeyanju, A., Radwan, G.L., Prom, L.K., and Magill, C.W. 2012. Sorghum pathology and biotechnology - A fungal disease perspective: Part II. Anthracnose, stalk rot, and downy mildew. *Eur. J. Plant Sci. Biotechnol.* 6(Special Issue 1):31-44.

- Toda, M., Beer, K.D., Kuivila, K.M., Chiller, T.M., and Jackson, B.R. 2021. Trends in agricultural triazole fungicide use in the United States, 1992–2016 and possible implications for antifungal-resistant fungi in human disease. *Environ. Health Perspect.* 129(8). <https://doi.org/10.1289/EHP7484>.
- U.S. Department of Agriculture, National Agricultural Statistics Service. 2025, January. Crop production 2024 summary. https://www.nass.usda.gov/Publications/Todays_Reports/reports/cropan25.pdf.
- Zaccaron, M., Holland, R., Gbur, E., Thompson, K., Rojas, J. A., & Rupe, J. C. (2024). Effect of drought stress during seed development on charcoal rot and yield of soybean. *Plant Disease*, 108(11), 3258–3268. <https://doi.org/10.1094/PDIS-07-23-1395-R>.
- Zhang, Q., Hua, X., Shi, H., Liu, J., Tian, M., and Wang, M. 2015. Enantioselective bioactivity, acute toxicity and dissipation in vegetables of the chiral triazole fungicide flutriafol. *J. Hazard. Mater.* 284:65-72. <https://doi.org/10.1016/j.jhazmat.2014.10.033>.

Tables and Figures

Table 2.1 Characteristics of field treatments in Bavaria, Russell and Dighton, Kansas, in 2023 and 2024.

Treatment list	Commercial name	Active ingredient	Fungicide timing	Application technology ^z	Fungicide rate (L ha ⁻¹)
T1	-	-	-	-	-
T2	Xyway™ LFR®	Flutriafol	At planting	2'2	1.11
T3	Xyway™ LFR®	Flutriafol	At planting	0'0	1.11
T4	Xyway™ LFR®	Flutriafol	At planting	0'2	1.11
T5	Xyway™ LFR®	Flutriafol <i>fb.</i>	At planting	2'2 <i>fb.</i>	0.77
	<i>fb.</i> Topguard® EQ	Flutriafol + Azoxystrobin	<i>fb.</i> Flowering	Foliar spray	0.37
T6	Topguard® EQ	Flutriafol + Azoxystrobin	Flowering	Foliar spray	0.37
T7	Topguard® EQ	Azoxystrobin + Fluindapyr Flutriafol	Flowering	Foliar spray	0.58

^z Banded dribbled 5.08 cm off-center below the row (2'2), dribbled over the row (0'0), or dribbled 5.08 cm off the row (0'2).

Table 2.2 Main effects and interactions for yield, panicle length, protein content, disease severity, incidence, and lodging data for Bavaria, Dighton, and Russell, Kansas.

Source	d.f. ^t	Yield (kg ha ⁻¹) ^u	Panicle length (cm) ^v	Protein (%) ^w	Severity (%) ^x	Incidence (%) ^y	Lodging (%) ^z
Hybrid (H)	1	0.0563*	0.7473	0.2915	0.3374	0.5884	0.7044
Location (L) ^r	3	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	.
H × L	3	0.7943	<.0032*	0.4238	0.4429	0.4304	.
Fungicide (F) ^s	6	0.0003*	0.9395	0.6032	0.1241	0.7823	0.7907
H × F	6	0.4920	0.3156	0.5906	0.4155	0.2854	0.7145
F × L	18	0.0209*	0.2997	0.6145	0.1186	0.6622	.
H × F × L	18	0.3676	9.5483	0.6532	0.8191	0.3376	.

*Significant at $\alpha = 0.05$.

^r Locations: Russell, Bavaria, and Dighton, KS.

^s Fungicide application.

^t Degrees of freedom.

^u Grain yield was adjusted to 15.0% moisture and determined from the 2nd and 3rd rows of each plot.

^v Panicle length of 10 plants per plot were measured.

^w Protein content.

^{x,y} Severity and incidence was assessed on 10 plants per plot prior to harvest.

^z Lodging was assessed at the plot level and was observed only in Dighton.

Table 2.3 Effects of environment on sorghum panicle length (cm), protein content (%), yield (kg ha⁻¹), disease incidence and severity (%).

Locations	Year	Panicle length (cm) ^v	Protein content (%)	Yield (kg ha ⁻¹) ^x	Incidence (%) ^y	Severity (%) ^z
Dighton	2024	12.38	11.85	2819.03	49.97	62.59
Bavaria	2024	10.08	10.92	4312.66	86.78	61.52
Russell	2024	11.77	7.87	5996.31	76.07	50.54
Russell	2023	12.11	-	5618.11	-	-
<i>P</i> -value*		< 0.0001	< 0.0001	< 0.0001	0.0002	< 0.0001

^v Panicle length of 10 plants per plot were measured. Plants were randomly collected from rows 1 and 4.

^x Grain yield was adjusted to 15.0%

^{y,z} Severity and incidence was assessed on 10 plants per plot prior to harvest randomly collected from rows 1 and 4.

*Significant at $\alpha = 0.05$.

Table 2.4 Average grain sorghum yield (kg ha⁻¹) response to fungicide application across locations and years.

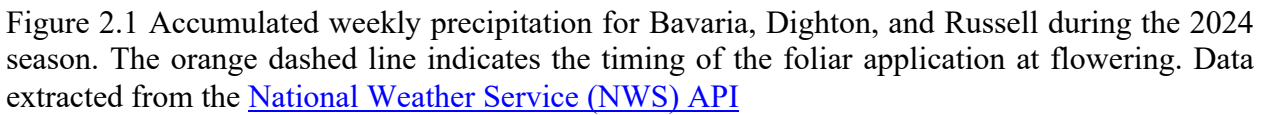
Treatments ^x	Yield (kg ha ⁻¹)			Yield (kg ha ⁻¹)
	2024 season			2023 season
	Bavaria	Dighton	Russell	Russell
T1	4051.38	2608.53	5867.28	5749.99
T2	3925.50	2899.16	6133.29	6289.74
T3	4418.11	2839.06	6376.70	6580.79
T4	4279.79	2813.25	5211.35	6141.83
T5	4310.51	2984.04	5713.32	5483.42
T6	4469.80	2898.72	6530.03	6374.30
T7	4733.53	2690.44	6142.21	6833.61

^x (T1) Non treated control, (T2) Xyway at planting with banded 2'2, (T3) dribbled over the row (0'0), (T4) Xyway dribbled 2 inches off the row (0'2), (T5) Xyway with banded 2'2 + Topguard EQ at flowering, (T6) Topguard EQ at flowering, and (T7) Adastrio at flowering.

Table 2.5 Sorghum grain yield average (kg ha⁻¹), marginal net return (\$ ha⁻¹), and profitability of fungicide applications (break-even points (kg ha⁻¹)).

Fungicide	Application technology	Yield (kg ha ⁻¹)	Marginal net return (\$ ha ⁻¹) ^x	Yield differences (kg ha ⁻¹)	Break-even points (kg ha ⁻¹) ^y
Non-treated control	-	4432.67	844.3	-	-
Xyway™ LFR®	At-planting	4662.75	838.9	230.08	259.4
Xyway™ LFR®	At-planting	4898.10	883.8	465.43	259.4
Xyway™ LFR®	At-planting	4466.52	801.5	33.85	259.4
Xyway™ LFR®	<i>fb.</i> At-planting	4492.80	784.4	60.13	601.1
Topguard® EQ	<i>fb.</i> Flowering	4917.41	879.0	484.74	341.6
Topguard® EQ	Flowering	4937.87	870.5	505.20	406.4
Adastrio™	Flowering				

The average grain sorghum price in 2024 was \$0.1905 kg ha⁻¹. The estimated average cost for Xyway™ LFR® was \$49.42 ha⁻¹, Topguard® EQ \$37.07 ha⁻¹, and Adastrio™ \$49.42 ha⁻¹. The estimated cost for aerial fungicide application was \$20.98 ha⁻¹. ^x Marginal Net Return = (Yield (kg/ha) × Price (kg)) – Fungicide Cost (/ha). ^y The break-even yield point was calculated based on: [(fungicide cost + application cost)/grain sorghum price].



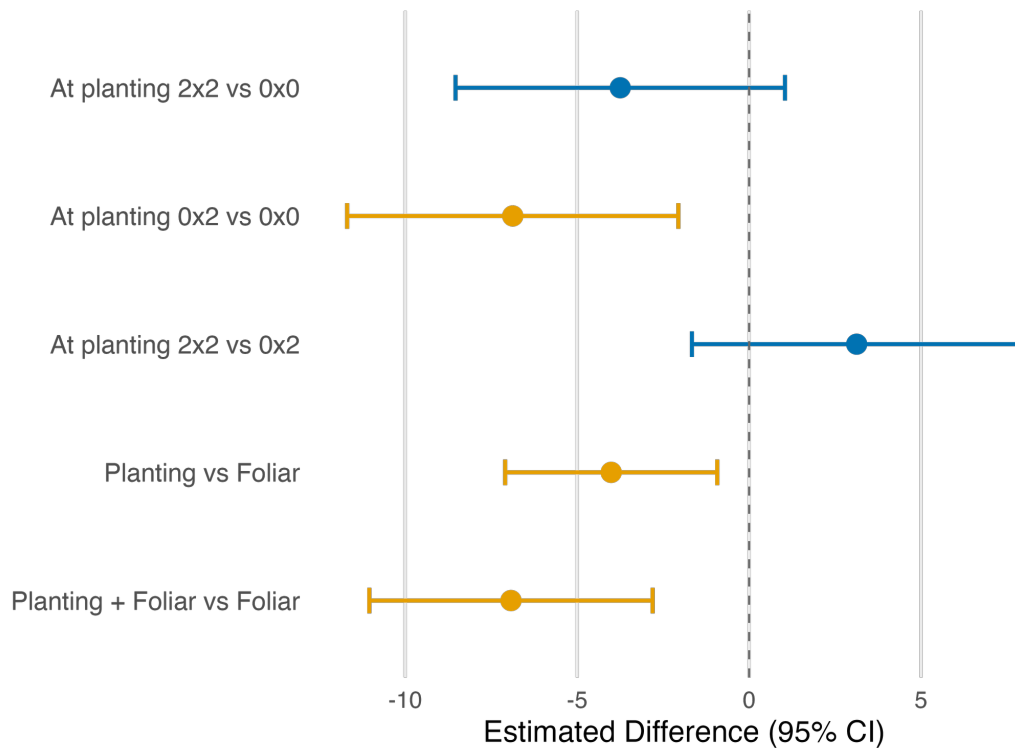


Figure 2.2 A linear contrast analysis among spray technology and fungicide application timing (at planting or flowering) for sorghum grain yield. Estimates represent the mean differences in yield between specified treatment groups, with dots showing contrast estimates and horizontal lines representing 95% confidence intervals (CI). Contrasts include: (i) at planting 2×2 vs at planting 0×0, (ii) at planting 0×2 vs at planting 0×0, (iii) at planting 2×2 vs. at planting 0×2, (iv) at planting vs. foliar application, and (v) planting + foliar application vs. foliar application.

Appendix A - Supplementary table

Table A.1. Dates of planting, harvest, foliar application, and seeding rates for sorghum experiments conducted at three locations in Kansas during the seasons 2022/23 and 2023/24.

Location	Year	Planting date ^w	Seeding Rate (seeds per ha ⁻¹)	Foliar application	Harvest date
Bavaria	2024	5/29/2024	55,000	8/14/2024	10/24/2024
Dighton	2024	5/27/2024	32,000	8/8/2024	10/26/2024
Russell	2024	5/26/2024	45,000	8/8/2024	10/25/2024
Russell	2023	5/31/2023	45,000	8/7/2023	10/20/2023

^w Treatments T2) Xyway at planting with banded 2x2, T3) Xyway dribbled over the row (0X0), T4) Xyway dribbled 2 inches off the row (0x2), T5) Xyway with banded 2x2, were applied at planting in each location.

Chapter 3 - Effects of Plant Density and Row Spacing on Sorghum Stalk Rot and Grain Yield Under Environmental Stress

3.1 Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is considered a resilient crop with potential to substitute common cereals like corn, rice, and wheat in everyday meals due to its nutritional composition and potential as a functional food (Aguiar et al., 2023). As a result, in 2025, the sorghum grain planted area in the U.S was estimated at 6.64 million acres, with production reaching 437 million bushels, an increase of 27 percent from the 2024 total of 343.85 million bushels (NASS, 2025). This increase was primarily supported by higher grain yields rather than changes in planted area.

Sorghum grain yield can be negatively affected by the presence of diseases, particularly stalk rot. Stalk rot complex are among the most important diseases affecting sorghum production across the US. It has been reported that under stressful conditions, such as drought, yield losses due to stalk rot and lodging can reach up to 60% in high-yielding hybrids across Kansas, with annual economic losses overcoming \$15 million per year (Tesso et al., 2004). The predominant stalk rot diseases observed are charcoal rot, caused by *Macrophomina phaseolina* (Tassi) Goid and Fusarium stalk rot, caused by *Fusarium* spp., including *F. thapsinum* Klittich, J.F. Leslie, P.E. Nelson & Marasas (Little et al., 2018). Although the pathogens associated with the disease are distinct, research investigating resistance to stalk rot in grain sorghum has shown that phenotypic responses to infection are often significantly and positively correlated; for instance, disease severity measurements for *Fusarium thapsinum* and *Macrophomina phaseolina* exhibit a significant positive correlation across diverse sorghum genotypes (Adeyanju et al., 2015).

Stalk rot is a complex disease that can severely affect both the stalk's structural integrity and grain yield. Stalk rot commonly appears during the grain filling stage, and is characterized by the deterioration of pith tissue near the base of the stalk, leading to the death of the stalk's pith cells and potentially causing plant lodging (Bandara et al., 2017). While lodging is the most evident symptom caused by stalk rot, the pathogen's impact is often more insidious, and yield losses can also occur due to reduced panicle size, grain filling, and early head lodging. In addition, stalk rot reduces leaf greenness by reducing leaf chlorophyll content (Bandara et al., 2016). This reduction in chlorophyll content can be worsened by other factors, such as post-flowering stresses, such as the presence of foliar diseases, inadequate fertilization, high plant densities, root rots, or physical injuries (Pande & Karunakar, 1992). When the inoculum is present in the field, the occurrence of stalk rot, as with most plant diseases, is influenced by environmental conditions. For instance, dry conditions and high-temperature stress increase charcoal rot incidence, while conditions alternating between cool and moist weather during physiological maturity and dry and hot conditions after flowering tend to favor *Fusarium* stalk rot severity (Little et al., 2018). *Macrophomina phaseolina* germinates at high temperatures ranging from 30 to 35 °C and soil moisture below 60%, while the highest average mycelial radial growth of *Fusarium thapsinum* is observed at 25°C, with the minimum growth observed at 15°C (Kaur et al., 2012; Pena et al., 2020).

Although stalk rot has been recognized as a significant threat to sorghum production since the early 1990s, with substantial yield losses, a limited amount of research has been conducted to understand this disease (Tesso et al., 2004). No hybrid has complete immunity to stalk rot pathogens (Jardine, 2006). Indeed, developing resistant hybrids has been challenging due to the complexity of this pathosystem, which involves multiple pathogens and the effects of abiotic

stress. For example, limitations to breeding for stalk rot resistance include the inconsistencies in reproducing field environments since the incidence and severity of stalk rot are highly dependent on environmental factors (Adeyanju et al., 2015). Consequently, current management recommendations rely on pre-planting strategies such as selecting hybrids with good standability and “stay-green” characteristics, avoiding excessive planting densities, and early harvest to reduce lodging risk. However, excessive stay-green may delay end-of-season senescence, which can complicate harvest. Although the recommendations emphasize avoiding excessive planting densities, there is a production trend toward intensifying crop production by increasing plant densities and reducing row spacing to maximize yield potential. However, in practice, optimizing plant density and row spacing may result in a trade-off between yield gain and plant stability. In narrow rows, sorghum plants develop taller, thicker stems by spacing individual plants more evenly, whereas high density leads to thinner stems and up to a 20% reduction in stem diameter (Martin & Kelleher, 1984; Adams et al., 2015). Maintaining a good plant stability is essential for minimizing the susceptibility to stalk rot pathogens.

Studies in literature about these practices often focus on optimizing yield components, biomass production, resource efficiency, and how sorghum plants compensate under different plant densities and row spacing (Martin & Kelleher, 1984; Bhatt, 1995; Staggenborg et al., 1999; Adams et al., 2015; Ottman & Ray, 2018). However, there is still limited research investigating the effect of plant densities and row spacing on the development of stalk rot and its interaction with abiotic stresses. Therefore, the objective of this study was to evaluate how the interaction of different row spacings and plant densities influences sorghum grain yield, panicle size, protein content, stalk rot severity, and the probability of lodging under stress-inducing environmental conditions.

3.2 Materials and methods

3.2.1. Experimental site and design

Research trials were established in three farmer fields in Russell (Russell County), Dighton (Lane County), and Bavaria (Saline County), Kansas, during the 2024 and 2025 seasons. Based on 30-year climate normals (1991–2020), annual precipitation across these locations ranges from approximately 21 inches in western Kansas (Lane County) to 31 inches in central Kansas (Saline County), reflecting the west-to-east precipitation gradient characteristic of the region (IPSR, 2024). The sites were selected based on grower reports of historically high stalk rot pressure and recurring lodging problems, with the presence of stalk rot inoculum. A continuous grain sorghum cropping system was used at all locations. No artificial inoculation was performed. Trials were conducted under standard agricultural practices for each region.

The experiments were arranged with a 2x4 factorial treatment structure in a split-plot design with row spacing [38.1 and 76.2 cm (15 and 30 inches)] in the main plot and hybrid and plant population in the sub-plot, with four replicates. Target populations were tailored to each row spacing: for the 38.1 cm spacing, targets were 1.24×10^5 , 1.48×10^5 , 1.73×10^5 , and 1.98×10^5 plants ha⁻¹, while the 76.2 cm spacing was 6.18×10^4 , 9.88×10^4 , 1.36×10^5 , and 1.73×10^5 plants ha⁻¹. Instead of using the target plant population, the final stand was measured from each plot and included as a continuous covariate in the analysis. Pioneer® hybrids 85P75 and 84P72 were planted using a 4-row planter (Kincaid Equipment Manufacturing, Haven, KS). These hybrids were selected specifically because both are susceptible to stalk rot, isolating the effect of cropping practices and environmental influences on stalk rot development. Experimental plots were 3.04 m wide (4 rows/plot with 76.2 cm between each row) and 7.72 m long with alleys of 1.52 m width separating the plot ends.

3.2.2 Crop measurements and data analysis

Stalk rot severity was evaluated in ten plants per plot, which were randomly selected from the 1st and 4th rows of each plot prior to harvest. Stalks from the collected plants were split, and the severity of stalk rot was visually assessed on the bottom 25.4 cm (10 in) of the stalk. The panicle size of the same 10 plants was measured using a ruler, from the point where the panicle starts on the peduncle to the panicle tip. Grain yield was determined from the 2nd and 3rd rows of each plot using a plot combine harvester (Massey Ferguson Kincaid 8XP, Haven, KS). The total seed weight and seed moisture content were recorded and converted to yield in kilograms per hectare. Yield calculations were adjusted for moisture content and standardized to 15%.

3.2.3 Data analysis

Statistical analyses of sorghum grain yield, protein content, and panicle size were performed using Generalized Linear Mixed Models (GLMMs). The same set of predictors was used in all models. Fixed-effects included row spacing, hybrid, location, year, and their interactions as categorical predictors, and final stand as a continuous predictor. Final stand was used instead of planting rates to account for differences between the target planting rates and the actual field densities. Random-effects included experimental design components such as blocks and row-stripes, with the second being part of the whole plot. All random effects were assumed to be independent of each other and of the residual. A student's *t-distribution* was assumed for grain yield and protein content, while applying a Gaussian distribution for panicle size.

For stalk rot lodging (percentage of lodging in a plot) and stalk rot severity the data was analyzed using a generalized additive model (GAMLSS) with a zero-inflated beta distribution

(BEZI), to account for the excess of zeros in the data (Ospina & Ferrari, 2008). The zero-inflated beta distribution is a probability distribution that can be used for data with multiple zeros and a constraint on the remaining observations between 0 and 1. The zero-inflated beta distribution is defined with 3 parameters: The zero-inflation v_i models the probability of a structural zero (in this case, true absence of disease), the mean μ_i is the mean of the non-zero data (i.e., $0 < y_i < 1$) and it models the severity of the response specifically when it actually occurs, and the dispersion σ_i is the scale parameter accounting for the variation within the non-zero data. The complete set of statistical framework components for both models is provided in Appendix B.

To evaluate how environmental stress affected sorghum stalk rot, the atmospheric water deficit (AWD) was used (Sexton-Bowser and Patrignani, 2024). The AWD was defined as the difference between daily reference evapotranspiration (ET_0) and daily precipitation ($AWD = ET_0 - P$). The atmospheric water deficit was calculated for two developmental windows: flowering (half-boom; W1: 21 days before to 21 days after flowering) and grain filling (W2: from flowering to physiological maturity). In this study, ET_0 represents the evaporative demand of a well-watered hypothetical grass reference surface, calculated via the FAO-56 Penman-Monteith equation. Daily weather data, including precipitation and reference evapotranspiration, were retrieved from the Open-Meteo historical database. Both windows were based on the literature that reports more severe stalk rot for plants under water deficit during the post-flowering and grain-filling period (Seetharama et al., 1987).

To evaluate the mechanical drivers of lodging, wind patterns were analyzed during the late season period (W3). The maximum wind speed was calculated to represent high-intensity wind events during the period. All statistical analyses and data visualization were implemented using the glmmTMB and gamlss packages in R.

3.3 Results and discussion

This study investigated the effect of different plant densities under narrow (38.1 cm) and wide (76.2 cm) row spacing on sorghum grain yield, panicle size, and protein content under stalk rot pressure, as well as the probability of zero lodging and stalk rot and the conditional mean severity under environmental stress using a zero-inflated framework.

3.3.1 Grain yield response to management strategies

Significant main effects of year ($p < 0.0001$), location ($p < 0.0001$) were observed at a level of $\alpha = 0.05$ were observed. For instance, the 2025 season resulted in an estimated yield increase of 2,404 kg ha⁻¹ (95% CI: [1,934, 2,874]) compared to 2024. This trend aligns with sorghum production data in Kansas, where sorghum grain production increased by 38.46% in 2025 compared to 2024 (NASS, 2025). In addition, significant interactions were observed for row spacing $\times$ year ($p = 0.004$) and row spacing $\times$ location ($p < 0.001$), and hybrid $\times$ year ($p = 0.002$), suggesting that the effects of these management strategies were highly dependent on the specific location and growing season. Additionally, a significant location $\times$ year interaction ($p < 0.001$) highlights the variability across the study locations and growing conditions.

This yield variation across locations is largely explained by the strong precipitation gradient in Kansas, where Central Kansas receives higher rainfall than Western Kansas locations, thereby supporting higher yield potential (Presley et al., 2012). This was reflected in our results, where higher yields were observed in Bavaria, followed by Russell and Dighton on average in both seasons (**Figure 3.1**). In 2025, significantly higher yields were observed for hybrid 84P72, which outperformed hybrid 85P75 by 414 kg ha⁻¹ (95% CI: [208, 620]; $p < 0.001$). No significant difference was observed between hybrids in 2024 (estimate: -47.3 kg ha⁻¹; 95% CI: [-288, 193]).

In addition, yield was consistently higher with wider row spacing across locations in both seasons, especially under favorable conditions. While the yield benefits of wider row spacing were consistent across environments, the magnitude of this effect was dependent on specific conditions, as evidenced by the significant row spacing $\times$ year interactions. For instance, under stressful and drought conditions, as observed during the 2024 season, wider row spacing resulted in an increase of 627 kg ha⁻¹ (95% CI: [383, 871]; $p < 0.0001$) compared with narrow row spacing ($p = 0.0001$), whereas in a favorable year for grain production, as observed in 2025, wider spacing resulted in a larger yield increase of 1,097 kg ha⁻¹ (95% CI: [881, 1312]; $p < 0.0001$). In the literature, narrow row spacing usually results in higher yields under favorable conditions and in high-yield environments, particularly due to greater light and water-use efficiency (Staggenborg et al., 1999; Adams et al., 2015). However, in low-yield or drought-stressed environments, narrow rows provide no yield benefit and can actually increase water stress earlier in the season (Staggenborg et al., 1999). This is primarily explained due to narrow rows resulting in plants that are more evenly distributed in the field, maximizing early-season light interception and vegetative growth, increasing the transpiration rate, and the rapid depletion of the soil moisture profile before the plant reaches anthesis (Bullock et al., 1988; Fukai & Foale, 1988; Steiner, 1986). Sorghum plants can adapt even under ultra-wide row spacing (203 cm) with no negative effect on total dry biomass by developing heavier, thicker stalks and increasing tillering per plant (Ottman & Ray, 2018).

Final stand and sorghum yield were positively related in all locations ($p = 0.019$). For every 1,000 additional plants per ha⁻¹, an increase of 2.6 kg ha⁻¹ (95% CI: 0.64, 4.55) was observed on average, regardless of the row spacing or environment. A similar positive trend between plant density and yield was observed for sweet sorghum and maize, with increased plant density consistently leading to higher biomass yield (Fuksa et al., 2023; Godsey et al., 2012). The reduced

tillering and vegetative mass when grain sorghum plants are clumped (high localized plant density) potentially resulted in a higher harvest index, suggesting a higher proportion of biomass allocated to grain production (Thapa et al., 2017). Nevertheless, the interaction between plant density and row configuration has been inconsistent, and studies suggest that environmental conditions play a crucial role in determining the best planting configuration. For example, a study evaluating the effects of plant density and row spacing on sorghum yield in Texas reported that rainfall during panicle formation was the primary factor influencing if twin-row system produced higher yield than single rows; however, since sorghum plants can adapt well when planted at lower populations, lower densities did not always result in lower yields (Fernandez et al., 2012).

3.3.2 Yield components and grain quality

Panicle size was influenced by location ($p < 0.0001$), hybrid ($p = 0.004$), and row spacing ($p < 0.001$), but depended on the growing conditions as indicated by row spacing $\times$ year ($p = 0.002$) and hybrid $\times$ year ($p < 0.0001$) interactions. In 2024, wider row spacing resulted in significantly longer panicles than narrow rows in Bavaria ($p = 0.0051$), Dighton ($p < 0.001$), and Russell ($p < 0.001$), with increases of 0.55, 0.65, and 0.78 cm, respectively (**Figure 3.2**). In contrast, in 2025, panicle size did not differ across row spacings, suggesting that the observed yield increase may be attributable to grain filling rather than to larger panicles. Similar results were observed with longer panicles during a severe drought year compared to a favorable year (Szemerits et al., 2025).

Increasing the final stand did not have a significant effect on panicle size ($p = 0.5208$). Hybrid 85P75 maintained significantly larger panicles than hybrid 84P72 in the 2024 season across all locations, but no difference was found in 2025. The effect of row spacing on protein content was environmental dependent (i.e., row spacing $\times$ location, $p < 0.001$) and on the year (i.e., row spacing $\times$ year, $p = 0.056$), consistent with previous research (Strieder et al., 2008). During the

2024 season, higher protein content was observed for wider row spacing in Russell ($p < 0.001$) and Bavaria ($p = 0.004$). In 2025, wider row spacing resulted in a higher protein concentration ($p < 0.001$) only in Russell (**Figure 3.3**). In 2025, hybrid 85P72, which had a higher yield performance, had significantly lower protein concentration ($p < 0.001$) than hybrid 85P75, highlighting the well-known negative relationship between yield and grain protein concentration (Ross et al., 1981).

3.3.3 Factors influencing stalk rot establishment and severity

The Southern Great Plains is a semiarid region facing erratic precipitation conditions with erratic seasonal precipitation and variable growing-season length (Baumhardt et al., 2005). Having a greater proportion of precipitation pre-anthesis compared to post-anthesis is a common phenomenon in Kansas. When there is significant heat stress followed by heavy precipitation at the end of the season, it can increase stalk rot and the risk of lodging. Charcoal rot and *Fusarium* stalk rot are considered the primary stalk rot diseases associated with water stress conditions (Assefa et al., 2010). Additionally, under severe moisture stress, the incidence of stalk rot is often very high (Seetharama et al., 1987).

Growing conditions were the primary drivers of disease pressure in this study. As observed in **Figure 3.4**, the 2024 season experienced severe drought stress, resulting in high positive atmospheric water deficits (AWD), particularly in Dighton and Bavaria during the flowering period, where evaporative demand exceeded precipitation. In addition, during the grain fill period, all locations experienced high positive atmospheric water deficits. In contrast, the 2025 season had lower AWD during both the flowering and grain-filling periods. Correspondingly, the 2024 season was associated with higher disease intensity compared to 2025 ($p < 0.02$) across all locations. The atmospheric water deficit during flowering had a negative relationship with the probability of

observing no stalk rot symptoms (v ; $p < 0.0001$), indicating that as the AWD increases (i.e., higher drought stress), the likelihood of zero stalk rot severity significantly decreases (**Figure 3.5**). Similarly, higher plant densities increased the probability of observing no stalk rot ($p < 0.0366$), suggesting that higher density contributed to reducing disease establishment in this study. In addition, plant density was positively related to the dispersion parameter ($p < 0.01$), suggesting that higher plant densities are associated with greater variability in stalk rot severity, increasing the uncertainty.

The analysis of the severity in infected plants (μ), showed that the final stand had a negative relationship with disease severity ($p = 0.0331$), suggesting that higher plant populations significantly reduced disease severity on infected plants. Row spacing did not influence stalk rot severity. Additionally, the atmospheric water deficit (AWD) during grain filling showed a significant positive relationship with stalk rot severity ($p = 0.0483$), indicating that higher drought stress (increased atmospheric demand relative to precipitation) in this critical period was associated with higher disease severity. Conversely, lower AWD values, representing reduced drought stress, were associated with a decrease in stalk rot symptoms. Studies have reported that the development of charcoal rot increases in water-stressed plants (Diourte et al., 1995; Odvody & Dunkle, 1979). Location significantly influenced disease severity, with higher mean disease severity observed in Bavaria than in Dighton ($p < 0.001$) and Russell ($p = 0.0295$).

Hybrid susceptibility was environment dependent. While hybrid 85P75 resulted in lower disease across the locations and years ($p = 0.040$), in Dighton, it showed higher disease severity ($p < 0.001$).

3.3.4 Interactions of plant density and row spacing on lodging risk and severity

Lodging before harvest was highly dependent on the environment, since it was observed only in Dighton during the 2024 season with severe lodging levels. In contrast, during the 2025 season, lodging was not observed at any location. Consequently, because only one environment exhibited severe lodging, our inference for the conditional mean severity (μ) is constrained to that specific site-year, which limits the ability to assess site-to-site and yearly variation. While this represents a single environment under disease pressure, the BEZI model incorporates the 'zero' observations from all other site-years to characterize the environmental conditions under which lodging does not occur, providing information for estimating the probability of zero lodging (ν).

Stalk rot severity and wind patterns were the primary drivers increasing the probability of occurrence and severity of lodging before harvest in Dighton during the 2024 season. A negative relationship between stalk rot severity and the probability of zero lodging (ν) was observed ($p < 0.001$). This suggests that as stalk rot severity increased, the probability of observing zero lodging decreased, thereby increasing the overall risk of lodging (**Figure 3.6**). Moreover, when lodging did occur (μ), higher stalk rot severity directly resulted in more severe lodging levels ($p = 0.018$). Wind speed was also an important driver of lodging risk, as increasing the number of days with late-season high wind speed was associated with a lower probability of zero lodging ($p < 0.001$), thereby increasing the overall lodging risk in this study.

It is acknowledged that lodging can happen in the field in the absence of disease when drought stress and high wind speed are combined. However, when stalk rot pathogens are present, damage increases, even under low or intermediate wind speeds. As observed by Adorada (2023), there is a quadratic relationship between the number of infected plants and the lodging rate, with lodging increasing as charcoal incidence increases. However, the study emphasizes that lodging incidence

is dependent on local weather conditions. Similarly, in a study investigating specific genomic regions and genetic markers associated with resistance to stalk rot in grain sorghum, it was found that stalk rot development is highly dependent on localized environmental stress (Robertson et al., 2020). In addition to abiotic stress, mechanical factors play a vital role; for example, maximum wind speed is a critical determinant of sorghum lodging, as it represents the external force required to exceed the stem's strength and lead to lodging events in both sorghum and other crops like wheat (Zargar et al., 2021; Niu et al., 2016).

Increasing plant density demonstrates contrasting effects on lodging events. When lodging occurred in the field (μ), the final stand had a significant effect ($p < 0.001$), with higher plant populations significantly reducing lodging severity in Dighton. Conversely, a strong positive relationship was observed between plant density and the dispersion parameter ($p < 0.0001$), suggesting that while higher density reduced the mean lodging severity, the uncertainty increased, reflecting the unpredictability of lodging.

We suspect that the reason for the higher lodging severity in lower plant densities in this study is related to greater tiller production. For instance, it is known that in sorghum, tiller production often compensates for planting density (Hoffmann & Rooney, 2014). At high localized plant density, tiller production is reduced compared to a lower, more uniform localized plant density, mainly due to less available growing space and reduced light transmission into the base of the plants (Thapa et al., 2017; Baumhardt et al., 2005; Godsey et al., 2012). This increased tiller production results in a higher number of panicles per plant, leading to intense remobilization of stalk carbohydrates and increased total plant weight. Furthermore, there is a positive correlation between stem lodging scores and internode rigidity, highlighting the importance of stalk rigidity to prevent stems from bending and lodging (Gomez et al., 2017).

While high plant densities are often associated with lodging due to canopy shading and the development of longer, thinner internodes, our experimental population likely did not reach the threshold necessary to trigger these negative effects (Yu et al., 2021). For context, previous studies investigating sorghum stalk rot found the highest incidence of charcoal rot occurred under a combination of high plant population (266,700 plants ha⁻¹) and drought stress (Pande et al., 1990). In contrast, the plant density observed in this experiment ranged only from 59,000 to 160,000 plants ha⁻¹.

Although previous findings suggest that narrow row spacing has advantages by improving the plant distribution and better use of resources (Strieder et al., 2008), under the conditions of this study, wider row spacing significantly reduced lodging severity compared to narrow row spacing ($p = 0.011$). Hybrid 85P75 showed significantly higher lodging severity compared to 85P72 ($p = 0.002$).

Future research is needed to determine the stress levels required to trigger susceptibility to stalk rot and whether the disease can occur at any growth stage under predisposed conditions. In addition, research should quantify the effects of stalk rot disease on grain yield and determine whether non-senescent or non-tillering sorghum plants respond differently to changes in plant density and row spacing. Furthermore, our findings show a correlation between disease severity and lodging and identify key environmental drivers of stalk rot. These drivers can be used to develop models that focus on predicting disease severity, rather than its incidence, enabling us to make more reliable inferences about the risk of lodging and helping growers make informed decisions and minimize losses. However, a current limitation is that these predictions were built under limited information. While the generalized additive model (GAMLSS) with a zero-inflated (BEZI) distribution used in this study was adequate to represent the conditional mean of stalk rot

and lodging severity when these events occurred, in order to increase inferential power, additional data across multiple regions and seasons should be incorporated, especially for lodging risk. An alternative to the collection of new data is to adopt a Bayesian approach.

3.4 Conclusion

This study evaluated the influence of final stand and row spacing configurations on sorghum stalk rot, lodging risk, and yield. Overall, yield was consistently higher with wider row spacing and showed a positive linear relationship with final stand across locations. Regarding disease, the probability of observing no stalk rot symptoms increased with higher plant density and lower drought stress during flowering, while severity was reduced by higher densities and lower stress during grain filling. Although lodging was observed only in one environment, limiting the assessment of yearly variation, stalk rot severity and wind speed were identified as the primary drivers of occurrence. In cases where lodging occurred, higher plant densities and wider row spacing significantly reduced lodging severity, whereas higher stalk rot severity directly increased the proportion of lodged plants.

References

- Adams, C. B., Erickson, J. E., Campbell, D. N., Singh, M. P., & Rebolledo, J. P. (2015). Effects of row spacing and population density on yield of sweet sorghum: Applications for harvesting as billets. *Agronomy Journal*, 107, 1831–1836. <https://doi.org/10.2134/agronj14.0295>
- Adeyanju, A., Little, C. R., Yu, J., & Tesso, T. (2015). Genome-wide association study on resistance to stalk rot diseases in grain sorghum. *G3: Genes, Genomes, Genetics*, 5(6), 1165–1175. <https://doi.org/10.1534/g3.114.016394>
- Adorada, D. L. (2023). Assessing PREDICTA®B as a potential disease risk management decision tool for sorghum charcoal rot based on disease levels, lodging, and associated yield loss. *Agronomy*, 13(10), 2494. <https://doi.org/10.3390/agronomy13102494>
- Aguiar, E. V., Santos, F. G., Queiroz, V. A. V., & Capriles, V. D. (2023). A decade of evidence of sorghum potential in the development of novel food products: Insights from a bibliometric analysis. *Foods*, 12, 3790. <https://doi.org/10.3390/foods12203790>
- Assefa, Y., Staggenborg, S. A., & Prasad, V. P. V. (2010). Grain sorghum water requirement and responses to drought stress: A review. *Crop Management*. <https://doi.org/10.1094/CM-2010-1109-01-RV>
- Bandara, Y. M. A. Y., Weerasooriya, D. K., Tesso, T. T., & Little, C. R. (2016). Stalk rot fungi affect leaf greenness (SPAD) of grain sorghum in a genotype- and growth-stage-specific manner. *Plant Disease*, 100(10), 2062–2068. <https://doi.org/10.1094/PDIS-02-16-0171-RE>
- Bandara, Y. M. A. Y., Weerasooriya, D. K., Tesso, T. T., Prasad, P. V. V., & Little, C. R. (2017). Impacts of fungal stalk rot pathogens on physicochemical properties of sorghum grain. *Plant Disease*, 101(12), 2059–2065. <https://doi.org/10.1094/PDIS-02-17-0238-RE>
- Baumhardt, R. L., Tolk, J. A., & Winter, S. R. (2005). Seeding practices and cultivar maturity effects on simulated dryland grain sorghum yield. *Agronomy Journal*, 97(3), 935–942.
- Bhatt, R. K. (1995). Light interception, leaf area index and dry matter yield in fodder sorghum at different plant populations. *J. Agronomy & Crop Science*, 174, 287–290. <https://doi.org/10.1111/j.1439-037X.1995.tb01114.x>
- Bullock, D. G., Nielsen, R. L., & Nyquist, W. E. (1988). A growth analysis comparison of corn grown in conventional and equidistant plant spacing. *Crop Science*, 28, 254–258.
- Diourte, M., Starr, J. L., Jeger, M. J., Stack, J. P., & Rosenow, D. T. (1995). Charcoal rot (*Macrophomina phaseolina*) resistance and the effects of water stress on disease development in sorghum. *Plant Pathology*, 44(2), 196–202. <https://doi.org/10.1111/j.1365-3059.1995.tb02742.x>
- Fernandez, C. J., Fromme, D. D., & Grichar, W. J. (2012). Grain sorghum response to row spacing and plant populations in the Texas Coastal Bend Region. *International Journal of Agronomy*, 2012, Article 238634. <https://doi.org/10.1155/2012/238634>

- Fuksa, P., Hrevušová, Z., Szabó, O., & Hakl, J. (2023). Effect of row spacing and plant density on silage maize growth, dry matter distribution and yield. *Agronomy*, 13(5), 1117. <https://doi.org/10.3390/agronomy13051117>
- Fukai, S., & Foale, M. A. (1988). Effects of row spacing on growth and grain yield of early and late sorghum cultivars. *Australian Journal of Experimental Agriculture*, 28, 771-777.
- Godsey, C. B., Linneman, J., Bellmer, D., & Huhnke, R. (2012). Developing row spacing and planting density recommendations for rainfed sweet sorghum production in the Southern Plains. *Agronomy Journal*, 104(1), 280–286. <https://doi.org/10.2134/agronj2011.0289>
- Gomez, F. E., Muliana, A. H., Niklas, K. J., & Rooney, W. L. (2017). Identifying morphological and mechanical traits associated with stem lodging in bioenergy sorghum (*Sorghum bicolor*). *BioEnergy Research*, 10, 635–647. <https://doi.org/10.1007/s12155-017-9826-7>
- Hoffmann, Jr., L., & Rooney, W. L. (2014). Sorghum improvement for yield. In I. Ciampitti & V. Prasad (Eds.), *Sorghum: State of the art and future perspectives* (Agronomy Monograph 58). ASA and CSSA. <https://doi.org/10.2134/agronmonogr58.2014.0055>
- Institute for Policy & Social Research, University of Kansas. (2024). *Kansas Statistical Abstract 2024*, 59th Edition. <https://ksdata.ku.edu/>
- Jardine, D. (2006). Stalk rots of corn and sorghum (Publication No. L-741). Kansas State University Agricultural Experiment Station and Cooperative Extension Service .
- Jin, R., Li, Z., Wang, X., Liu, F., Kong, F., Liu, Q., Lan, T., Feng, D., & Yuan, J. (2023). Optimizing row spacing increases stalk lodging resistance by improving light distribution in dense maize populations. *Agronomy*, 13, 462. <https://doi.org/10.3390/agronomy13020462>
- Little, C. R., Bandara, A., Todd, T. C., & Perumal, R. (2018). Sorghum diseases and their management in cultivation: Stalk, root and other diseases. In D. L. Sparks (Ed.), *Achieving sustainable cultivation of sorghum: Volume 1*. Burleigh Dodds Science Publishing.
- Morris, G. P., Ramu, P., Deshpande, S. P., Hash, C. T., Shah, T., et al. (2013). Population genomic and genome-wide association studies of agroclimatic traits in sorghum. *Proceedings of the National Academy of Sciences of the United States of America*, 110(2), 453–458. <https://doi.org/10.1073/pnas.1215985110>
- Niu, L., Feng, S., Ding, W., & Li, G. (2016). Influence of speed and rainfall on large-scale wheat lodging from 2007 to 2014 in China. *PLoS ONE*, 11(7), e0157677. <https://doi.org/10.1371/journal.pone.0157677>
- Odvody, G. N., & Dunkle, L. D. (1979). Charcoal stalk rot of sorghum: Effect of environment on host-parasite relations. *Phytopathology*, 69(3), 250–254. <https://doi.org/10.1094/Phyto-69-250>
- Pande, S., & Karunakar, R. I. (1992). Stalk rots. ICRISAT, Patancheru, India.
- Pande, S., Mughogho, L. K., & Karunakar, R. I. (1990). Effect of moisture stress, plant population density and pathogen inoculation on charcoal stalk rot of sorghum. *Annals of Applied Biology*, 116, 221–232.

- Pena, G. A., Sulyok, M., & Chulze, S. N. (2020). Effect of interacting conditions of water activity, temperature and incubation time on *Fusarium thapsinum* and *Fusarium andiyazi* growth and toxin production on sorghum grains. *International Journal of Food Microbiology*, 318, Article 108468. <https://doi.org/10.1016/j.ijfoodmicro.2019.108468>
- Presley, D., Shoup, D., Holman, J., & Schlegel, A. (Eds.). (2012). *Efficient crop water use in Kansas (MF3066)*. Kansas State University Agricultural Experiment Station and Cooperative Extension Service.
- Robertson, A. E., Serrano, M., Acharya, J., Shriver, J., Beckman, J., Huffman, C., Pecinovsky, K., Rees, M., Schaben, D., Schnabel, M., Sievers, J., & Tuttle, T. (2020). Effect of foliar fungicides applied at silking on stalk lodging in corn. *The American Phytopathological Society*.
- Ross, W. M., Kofoed, K. D., Maranville, J. W., & Voigt, R. L. (1981). Selecting for grain protein and yield in sorghum random-mating populations. *Crop Science*, 21(5), 774–777. <https://doi.org/10.2135/cropsci1981.0011183X002100050036x>
- Sexton-Bowser, S., & Patrignani, A. (2024). Yield gap analysis for rainfed grain sorghum in Kansas. *Agronomy Journal*, 116(6), 2901–2911. <https://doi.org/10.1002/agj2.21684>
- Seetharama, N., Bidinger, F. R., Rao, K. N., Gill, K. S., & Mulgund, M. (1987). Effect of pattern and severity of moisture deficit stress on stalk rot incidence in sorghum. I. Use of line source irrigation technique, and the effect of time of inoculation. *Field Crops Research*, 15(3-4), 289–308.
- Staggenborg, S. A., Fjell, D. L., Devlin, D. L., Gordon, W. B., & Marsh, B. H. (1999). Grain sorghum response to row spacings and seeding rates in Kansas. *Journal of Production Agriculture*, 12(3), 390–395.
- Steiner, J. L. (1986). Dryland grain sorghum water use, light interception, and growth responses to planting geometry. *Agronomy Journal*, 78, 720–726.
- Strieder, M. L., Silva, P. R. F., Rambo, L., Sangoi, L., Silva, A. A., Endrigo, P. C., & Jandrey, D. B. (2008). Crop management systems and maize grain yield under narrow row spacing. *Scientia Agricola*, 65(4), 346–353. <https://doi.org/10.1590/S0103-90162008000400004>
- Surinder Kaur, Gurpreet Singh Dhillon, Satinder Kaur Brar, Gary Edward Vallad, Ramesh Chand & Vijay Bahadur Chauhan (2012) Emerging phytopathogen *Macrophomina phaseolina*: biology, economic importance and current diagnostic trends, *Critical Reviews in Microbiology*, 38:2, 136-151, DOI: 10.3109/1040841X.2011.640977
- Szemerits, B., Kukorelli, G., Kabato, W. S., & Molnár, Z. (2025). Seed rate and row spacing effects on yield and quality of sorghum maturity groups under Central European conditions. *Seeds*, 4, 61. <https://doi.org/10.3390/seeds4040061>
- Tesso, T., Claflin, L. E., & Tuinstra, M. R. (2004). Estimation of combining ability for resistance to *Fusarium* stalk rot in grain sorghum. *Crop Science*, 44(4), 1195–1199. <https://doi.org/10.2135/cropsci2004.1195>

- Thapa, S., Stewart, B. A., Xue, Q., & Chen, Y. (2017). Manipulating plant geometry to improve microclimate, grain yield, and harvest index in grain sorghum. *PLoS ONE*, 12(3), e0173511. <https://doi.org/10.1371/journal.pone.0173511>
- United States Department of Agriculture, National Agricultural Statistics Service. (2025). Crop production 2024 summary. <https://downloads.usda.library.cornell.edu/usda-esmis/files/k3569432s/nk324887m/qn59s0097/cropan25.pdf>
- Yu, K. M. J., McKinley, B., Rooney, W. L., & Mullet, J. E. (2021). High planting density induces the expression of GA3-oxidase in leaves and GA mediated stem elongation in bioenergy sorghum. *Scientific Reports*, 11, 647. <https://doi.org/10.1038/s41598-020-79975-8>
- Zargar, O., Li, Q., Nwaobi, C., Pharr, M., Finlayson, S. A., & Muliana, A. (2021). Thigmostimulation alters anatomical and biomechanical properties of bioenergy sorghum stems. *SSRN*. <https://doi.org/10.2139/ssrn.3957953>

Figures

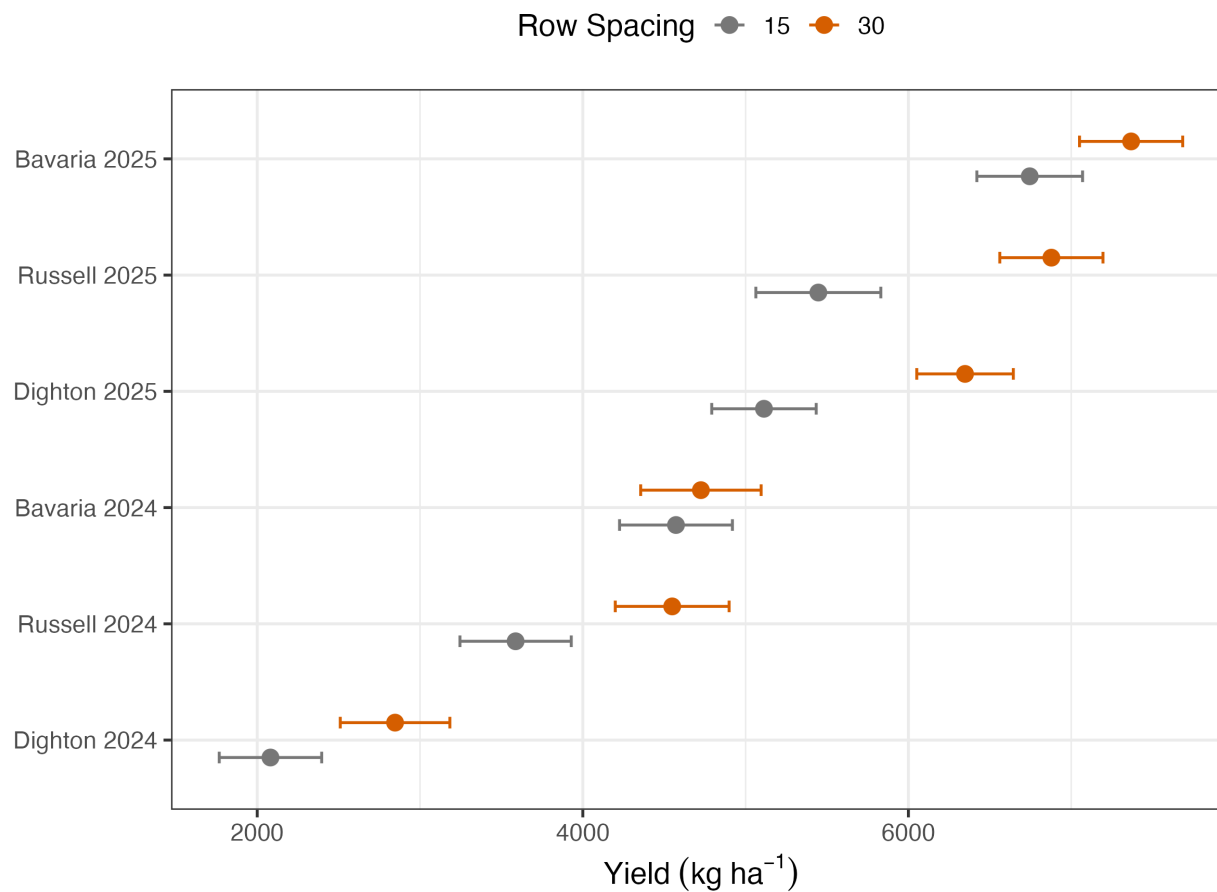


Figure 3.1 Estimated marginal means (95% CI) of sorghum grain yield (kg ha⁻¹) as influenced under narrow (38.1 cm; 15 in) and wide (76.2 cm; 30 in) row spacing across all site-years.

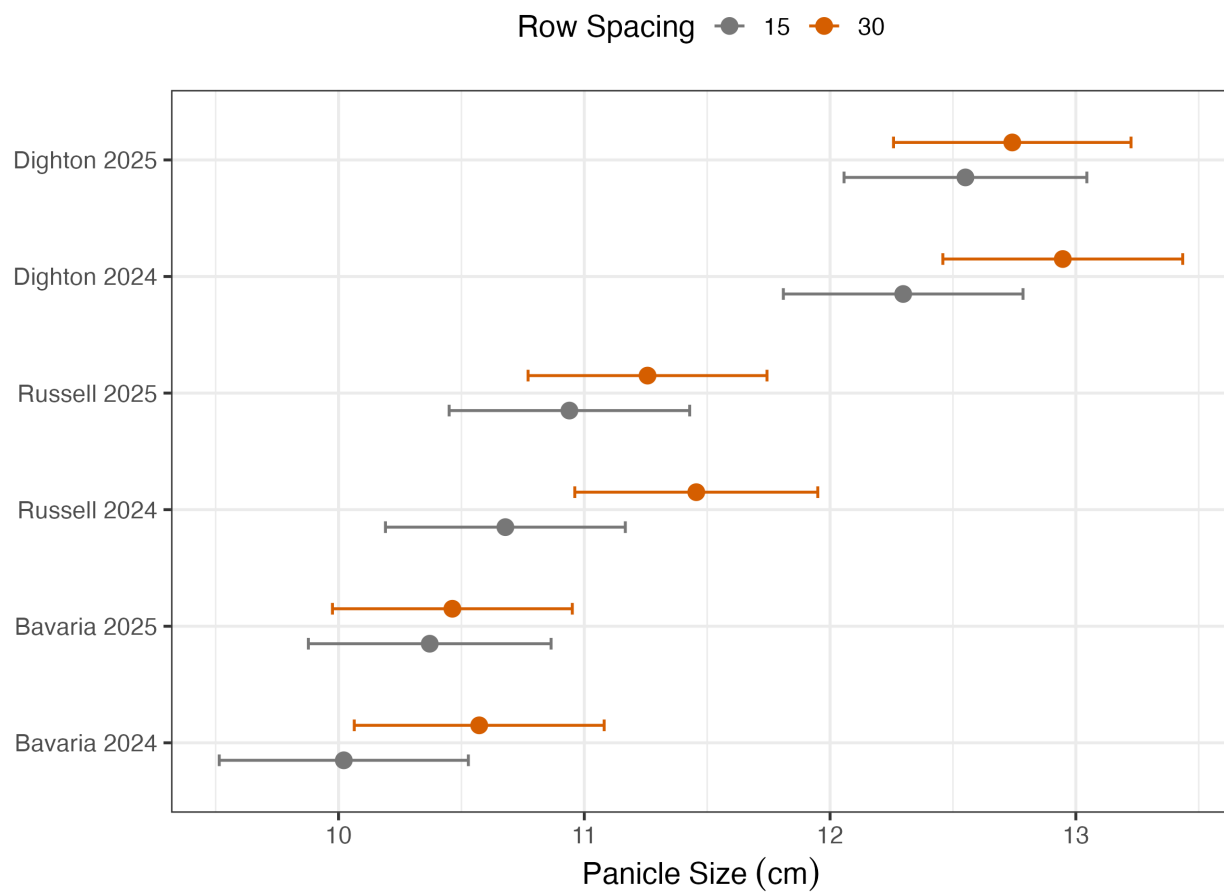


Figure 3.2 Estimated marginal means (95% CI) of panicle size (cm) as influenced under narrow (38.1 cm; 15 in) and wide (76.2 cm; 30 in) row spacing across all site-years.

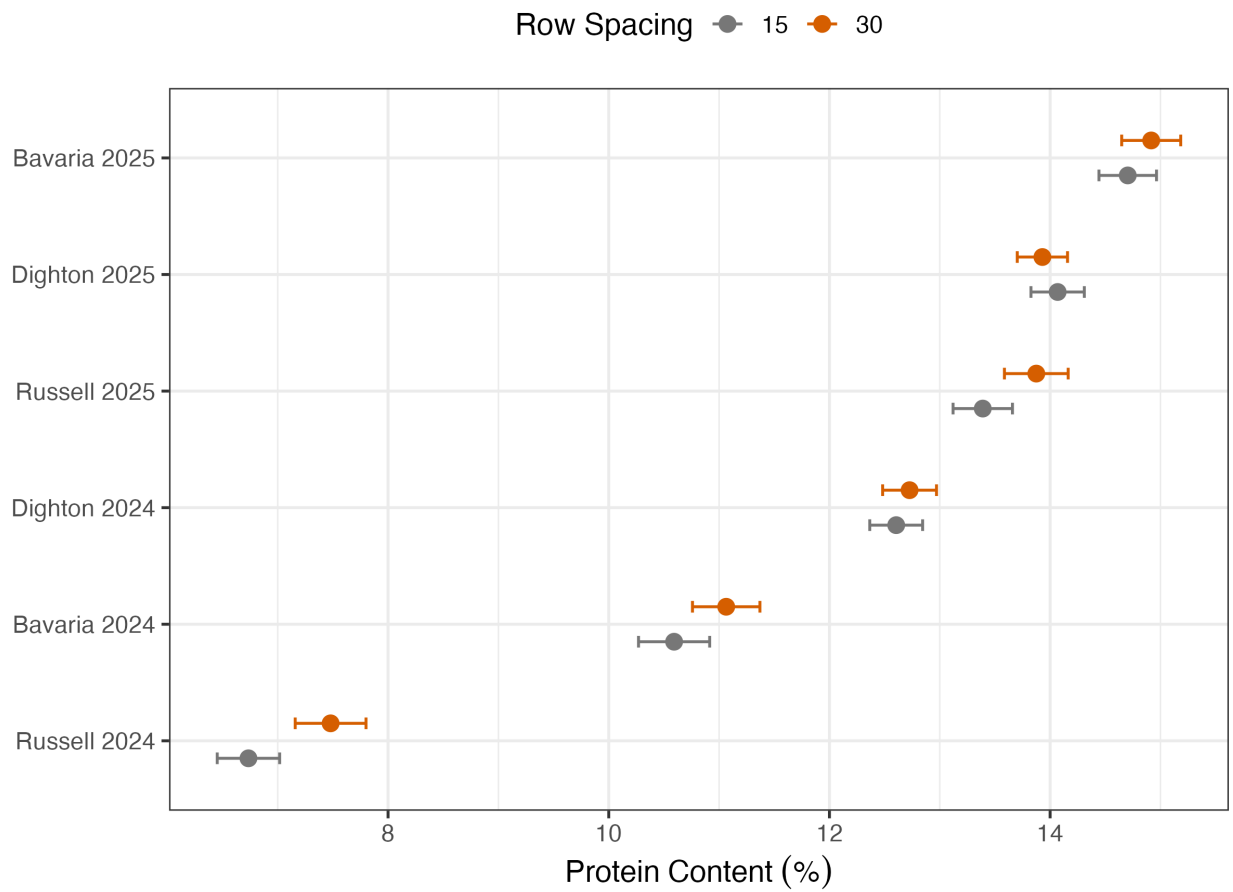


Figure 3.3 Estimated marginal means (95% CI) of grain protein content % as influenced under narrow (38.1 cm; 15 in) and wide (76.2 cm; 30 in) row spacing across all site-years.

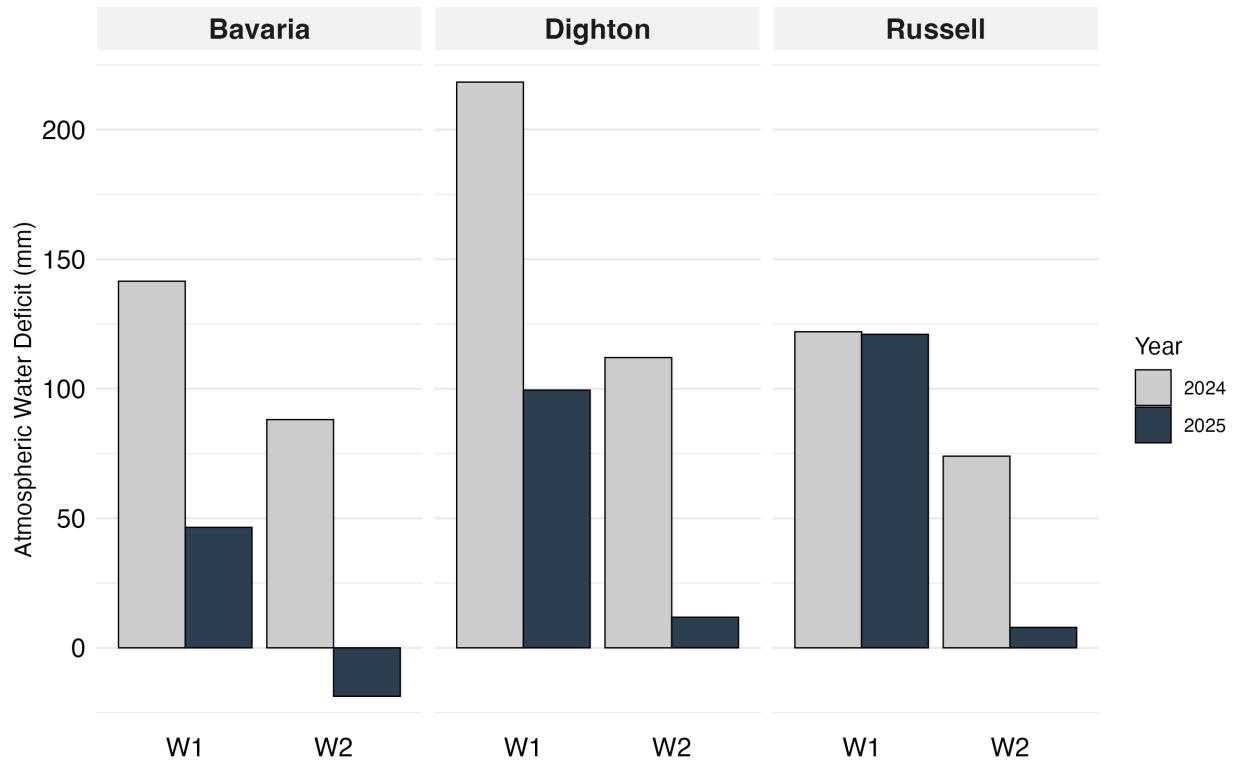


Figure 3.4 Atmospheric Water Deficit (AWD, mm) during flowering (W1) and grain fill (W2) across three Kansas locations (Bavaria, Dighton, and Russell) during the 2024 and 2025 growing seasons. Positive values indicate an atmospheric water deficit, representing drought stress conditions where evaporative demand exceeded precipitation.

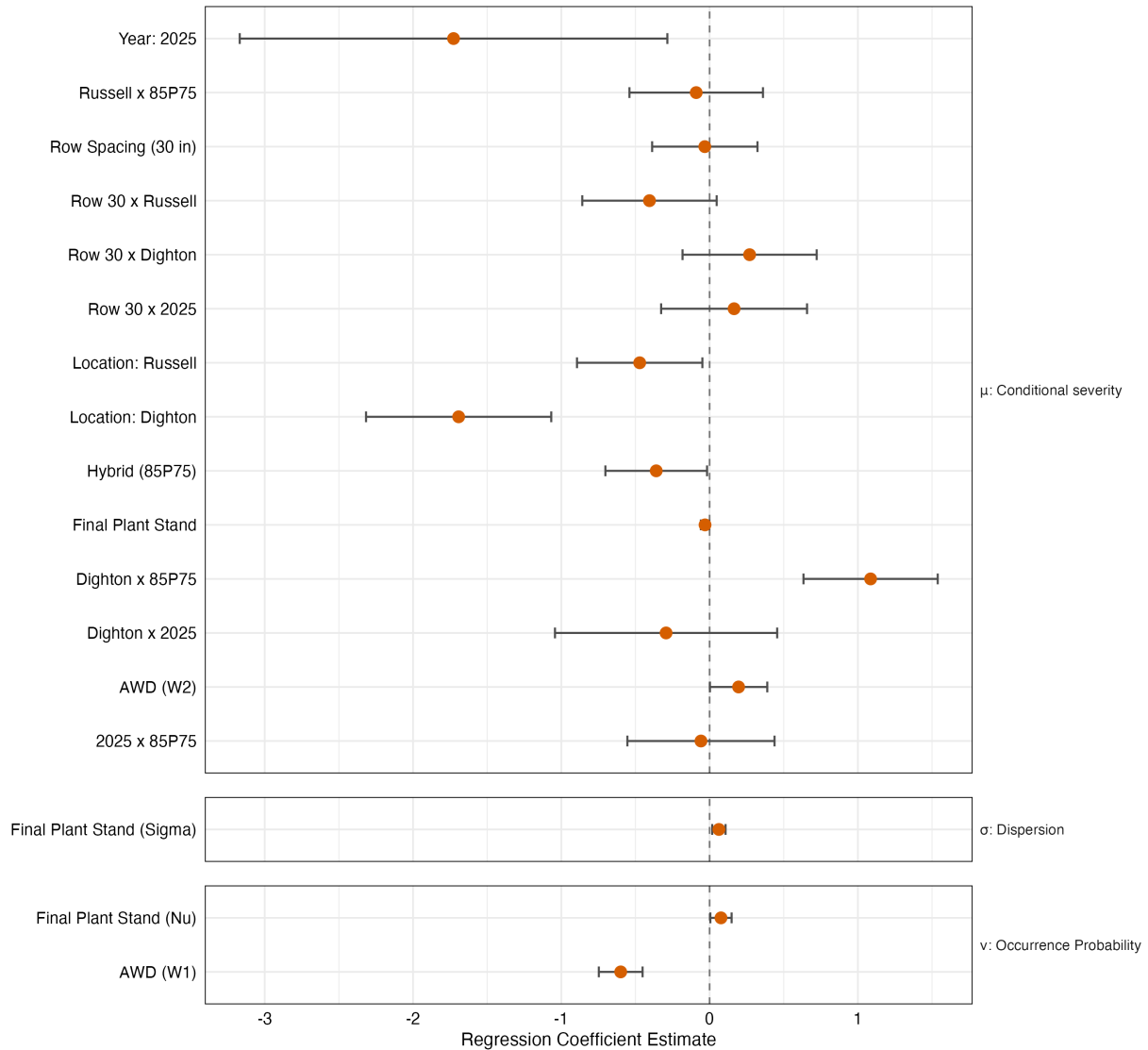


Figure 3.5 Regression coefficient estimates for stalk rot severity parameters (ν , μ , σ) in a Zero-Inflated Beta (BEZI) model. Values to the left of the dashed line (negative) indicate a decrease in the parameter, while values to the right (positive) indicate an increase. Error bars represent 95% confidence intervals.

* For visualization purposes, coefficients for Final Plant Stand and Water Balance have been scaled by a factor of 10, and the estimates reflect the predicted change in the response per 1×10^4 plants and per 10 units of water balance, respectively.

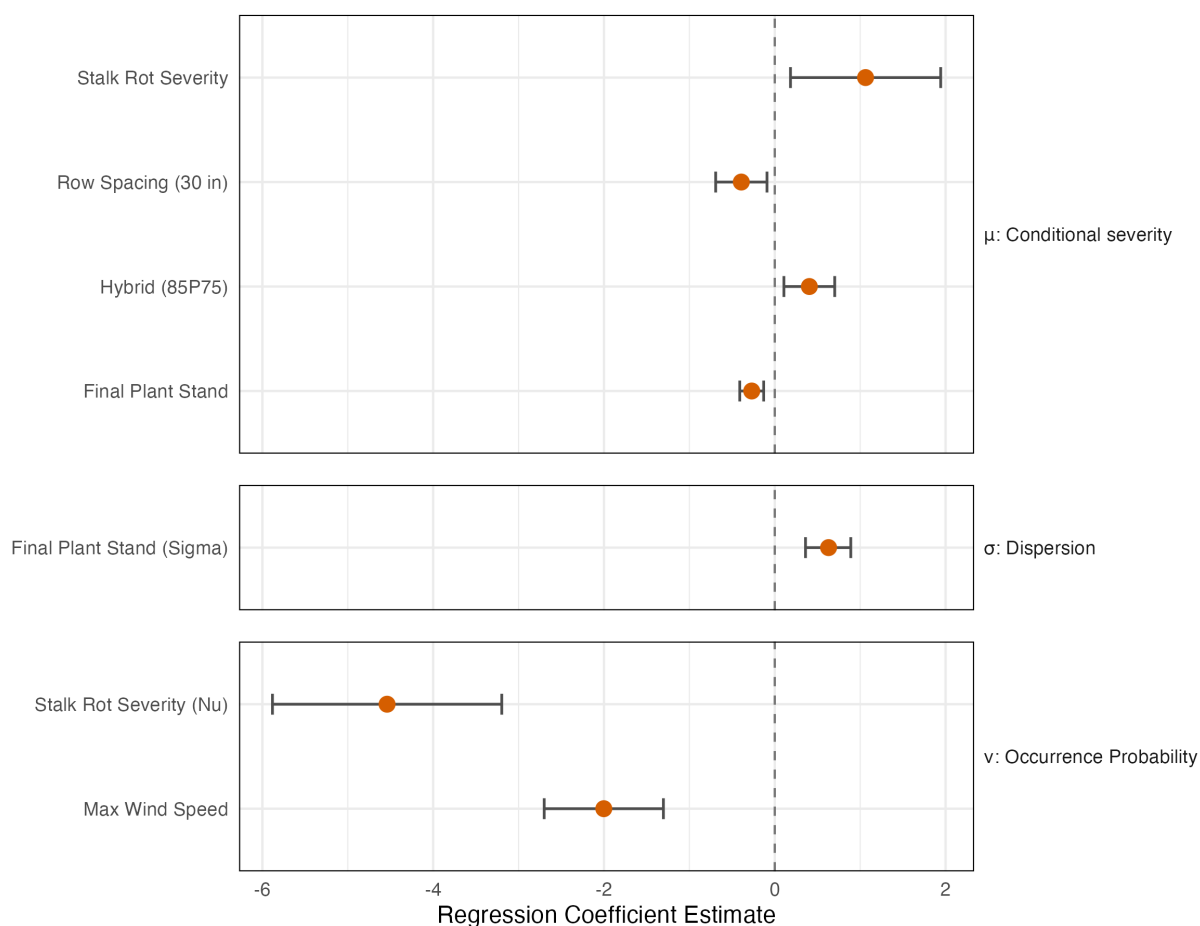


Figure 3.6 Regression coefficient estimates for lodging parameters (ν , μ , σ) in a Zero-Inflated Beta (BEZI) model. Values to the left of the dashed line (negative) indicate a decrease in the parameter, while values to the right (positive) indicate an increase. Error bars represent 95% confidence intervals.

* For visualization purposes, coefficients for Final Plant Stand and Water Balance have been scaled by a factor of 10, and the estimates reflect the predicted change in the response per 1×10^4 plants and per 10 units of water balance, respectively.

Appendix B - Statistical model specifications

The model can be expressed as:

$$y_i \sim BEZI (v_i, \mu_i, \sigma_i)$$

$$\mu_i =$$

$$v_i =$$

where: y_i is the response (lodging percentage or severity) for the i^{th} observation and was assumed to arise from a zero-inflated beta distribution. The zero-inflated beta distribution is defined with 3 parameters: The zero-inflation v_i models the probability of a structural zero (in this case, true absence of disease), the mean μ_i is the mean of the non-zero data (i.e., $0 < y_i < 1$) and it models the severity of the response specifically when it actually occurs, and the dispersion σ_i is the scale parameter accounting for the variation within the non-zero data.

a) Stalk Rot Severity Model:

$$\begin{aligned} \text{logit}(\mu_{ijkl}) = & \beta_{0\mu} + R_i + L_k + Y_l + (RL)_{ik} + (RY)_{il} + H_j + (HL)_{jk} + (HY)_{jl} + (LY)_{kl} \\ & + S + AWD_2 + b_{kl} + \mu_{ikl} \end{aligned}$$

$$b_{kl} \sim N(0, \sigma_b^2), \quad \mu_{ikl} \sim N(0, \sigma_\mu^2)$$

Where $\text{logit}(\mu_{ijkl})$ is the link function for the mean of the beta distribution, $\beta_{0\mu}$ is the overall mean, R_i is the effect of the i^{th} row spacing, H_j is the effect of the j^{th} hybrid, L_k and Y_l are the effects of location and year, and the subsequent terms represent their respective interactions. S is the fixed effect of the final plant stand, AWD_2 is the effect of atmospheric water deficit during grain filling. b_{kl} is the random intercept for Block nested within location and year; μ_{ikl} is the main plot error, representing the random effect of row spacing within blocks. Both random effects are assumed independent to each other and to the residual.

$$\text{logit}(v_i) = \beta_{0v} + AWD_{1i}\beta_{1v} + S_i\beta_{2v}$$

Where $\text{logit}(v_i)$ is the link function for the probability of observing a structural zero; AWD_{1i} is the effect of atmospheric water deficit during the flowering period, and S_i is the effect of the final plant stand.

$$\log(\sigma_i) = \beta_{0\sigma} + S_i\beta_{1\sigma}$$

Where $\log(\sigma_i)$ is the link function for the dispersion parameter; $\beta_{0\sigma}$ is the intercept, and S_i represents the effect of the final plant stand on the variability of the disease.

b) Lodging Severity Model:

$$\text{logit}(\mu_i) = \beta_{0\mu} + Sev_i + R_j + H_k + \beta_{S\mu}S_i + b_l + \mu_m$$

$$\mu_m \sim N(0, \sigma_\mu^2)$$

Where $\beta_{0\mu}$ is the overall mean, Sev_i is the effect of stalk rot severity, R_j is the j^{th} row spacing, H_k is the k^{th} hybrid, and S_i is the continuous effect of final plant stand. Since lodging was observed only in a single environment (Dighton, 2024), the random effects structure was simplified to include only a random intercept for the main plot.

$$\log(\sigma_i) = \beta_{0\sigma} + S_i\beta_{1\sigma}$$

Where $\log(\sigma_i)$ is the link function for the dispersion parameter; $\beta_{0\sigma}$ is the intercept, and S_i represents the effect of the final plant stand on the variability of the disease.

Appendix C - Regression coefficients table

Table C.1. Point and interval estimates for regression coefficients of BeZI (ν, μ, σ) distribution for stalk rot severity.

Parameter	Predictor	Estimate (β)	95% CI	<i>P</i> -value
μ (Severity)	Intercept	-0.376	(-2.130, 1.378)	0.671
	Row 30	-0.032	(-0.388, 0.323)	0.858
	Location:Dighton	-1.692	(-2.316, -1.068)	< 0.001
	Location:Russell	-0.472	(-0.894, -0.049)	0.030
	Year:2025	-1.731	(-3.169, -0.292)	0.020
	Hybrid:85P75	-0.360	(-0.703, -0.017)	0.040
	Final Stand	-0.003	(-0.006, -0.000)	0.033
	AWD (W2)	0.019	(0.000, 0.039)	0.048
	Row 30:Dighton	0.270	(-0.183, 0.722)	0.243
	Row 30:Russell	-0.405	(-0.859, 0.048)	0.080
	Row 30: 2025	0.165	(-0.327, 0.657)	0.511
	Dighton: 85P75	1.086	(0.633, 1.538)	< 0.001
	Russell: 85P75	-0.090	(-0.541, 0.360)	0.694
	2025:85P75	-0.058	(-0.554, 0.438)	0.818
	Dighton:2025	-0.293	(-1.043, 0.456)	0.443
σ (Dispersion)	Intercept	1.443	(0.890, 1.997)	<0.001
	Final Stand	0.006	(0.002, 0.011)	0.007
ν (Zeros)	Intercept	4.815	(2.593, 6.646)	< 0.001

AWD (W1)	0.060	(0.045, 0.075)	< 0.001
Final Stand	0.008	(0.001, 0.015)	0.037

Table C.2. Point and interval estimates for regression coefficients of BeZI (ν, μ, σ distribution for lodging).

Parameter	Predictor	Estimate (β)	95% CI	<i>P</i> -value
μ (Severity)	Intercept	-0.259	(-1.155, 0.637)	0.572
	Stalk rot severity	1.064	(0.184, 1.943)	0.018
	Row30	-0.392	(-0.692, -0.091)	0.011
	Hybrid85P75	0.405	(0.108, 0.702)	0.008
	Final Stand	-0.027	(-0.041, -0.013)	< 0.001
σ (Dispersion)	Intercept	-0.216	(-1.450, 1.017)	0.731
	Final Stand	0.063	(0.036, 0.089)	< 0.001
ν (Zeros)	Intercept	53.125	(35.358, 70.892)	< 0.001
	Stalk rot severity	-4.540	(-5.882, -3.197)	< 0.001
	Wind_Speed	-2.002	(-2.700, -1.304)	< 0.001

Appendix D - Model validation

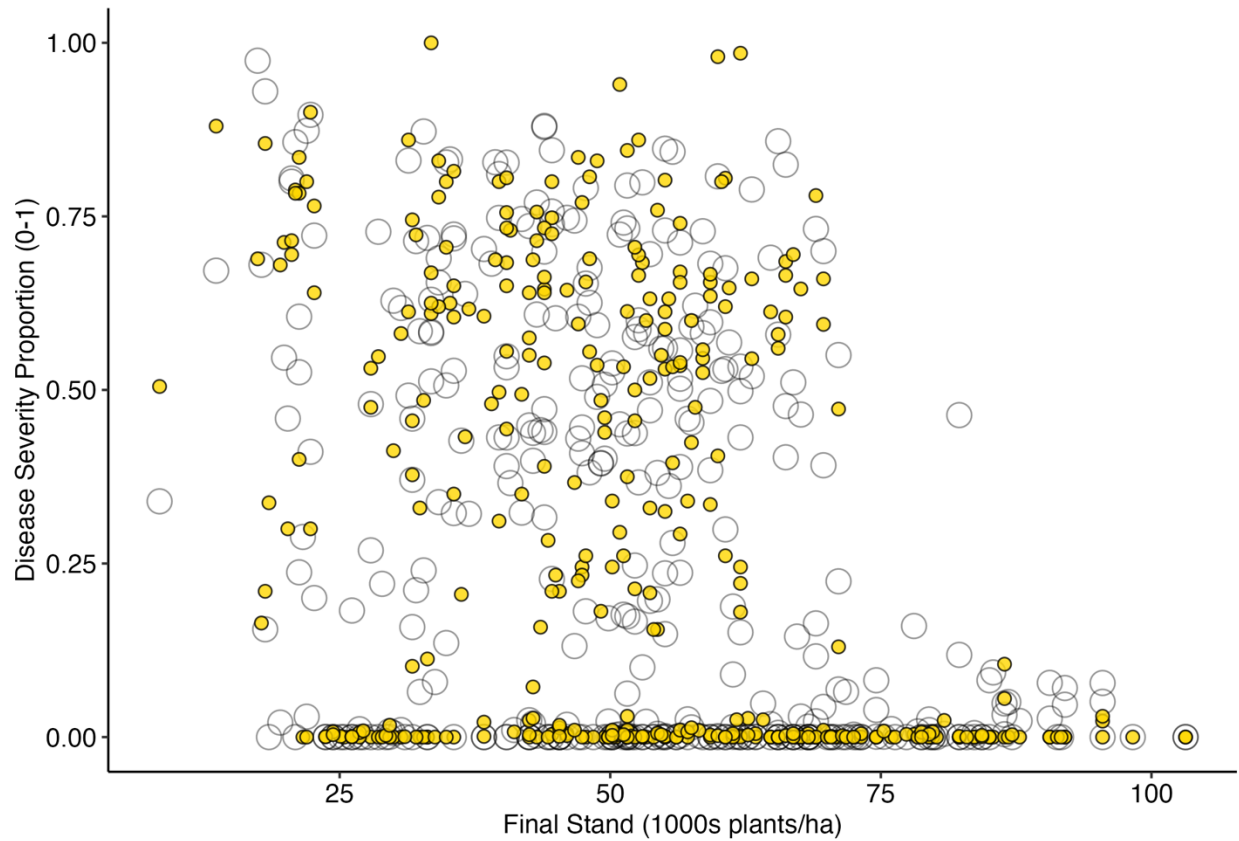


Figure D.1. Marginal model validation of sorghum stalk rot severity. Yellow circles represent the actual observed field data for stalk rot severity proportion (0–1 scale); open grey circles represent population-level simulated data points generated from the fitted regression model to assess goodness-of-fit.

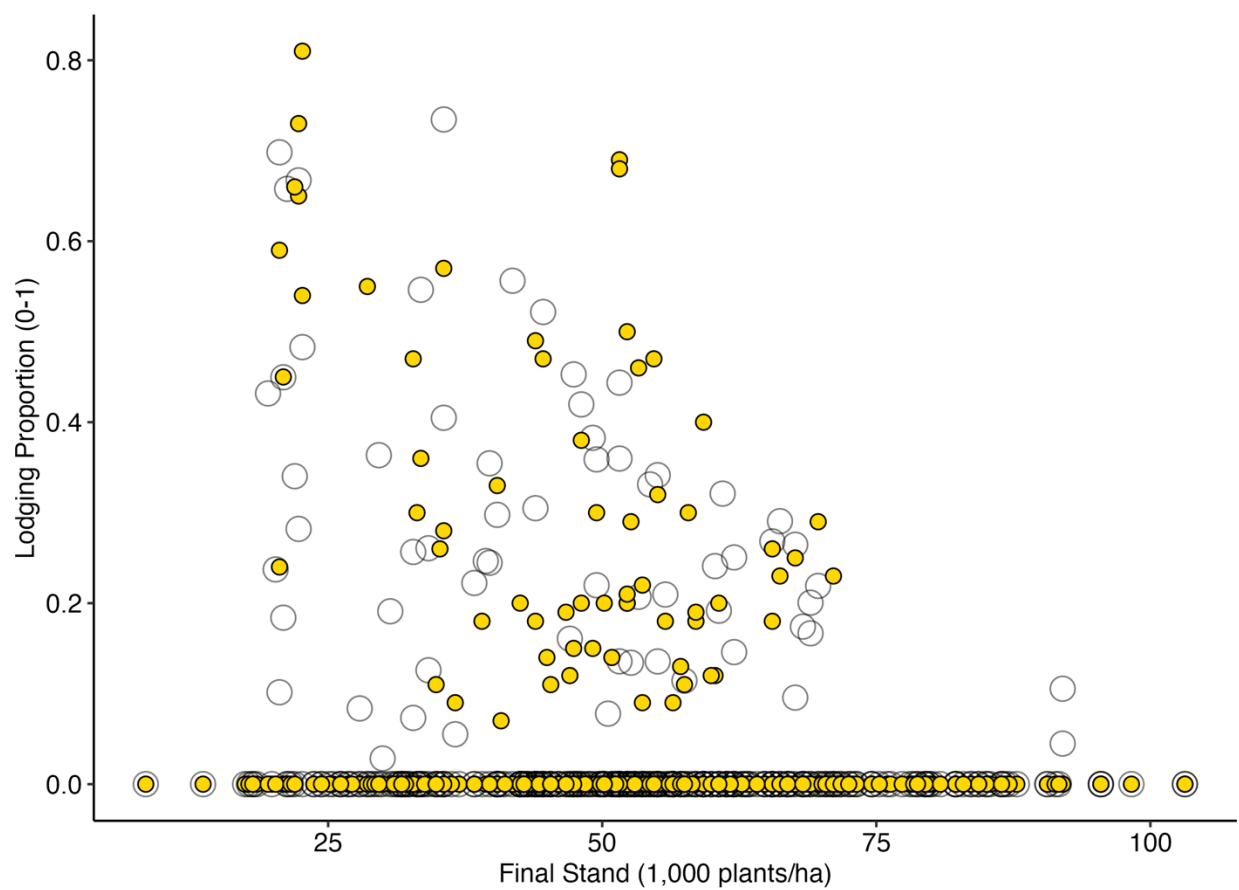


Figure D.2. Marginal model validation of sorghum lodging severity. Yellow circles represent the actual observed field data for stalk rot severity proportion (0–1 scale); open grey circles represent population-level simulated data points generated from the fitted regression model to assess goodness-of-fit.