Quantitative multifactor analysis of planter settings and row unit design for corn stand establishment in precision agriculture

by

Jose Peiretti

B.S., National University of Córdoba, 2003

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Biological and Agricultural Engineering
Carl R. Ice College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2025

Abstract

Achieving a uniform stand of corn (*Zea mays* L.) is paramount for maximizing yield potential and enhancing resource use efficiency. Despite considerable advancements in planting technologies, challenges associated with variability in seed placement accuracy, seed depth, and overall population uniformity persist. This variability is attributed to intricate interactions among planter operational parameters, soil heterogeneity, and the design of mechanical components. Critical factors, including planting speed, hydraulic downforce application, and row unit arrangement, significantly influence the quality of seed-to-soil contact and the integrity of furrow closure, which in turn affects early seedling emergence and final stand uniformity. Nonetheless, there exists a gap in the comprehensive understanding of optimal combinations of these factors, particularly in the context of varying environmental conditions and emerging adaptive hydraulic technologies. This doctoral research aims to address these challenges through a multifactorial analysis encompassing planter settings, hydraulic dual force control, and row unit component design. The study systematically evaluates the combined effects of these variables on seed placement precision, emergence dynamics, and population uniformity under diverse field conditions in North-central Kansas, USA. Utilizing John Deere ExactEmerge™ planters equipped with standard unidirectional and experimental dual hydraulic force control systems, the research varied planter speeds (ranging from 8 to 16 km h^{-1}), implemented discrete hydraulic downforce margins, and assessed multiple furrow-closing device types, including rounded and spiked rubber closing wheels, as well as more sophisticated devices incorporating discs and hydraulic pressure augmentation. The experimental design employed a rigorous split-split plot with randomized design methodologies to robustly capture treatment interactions. State-of-the-art instrumentation facilitated real-time acquisition of hydraulic pressures, mechanical load data, and spatial seed placement metrics, thereby enhancing data resolution. A comprehensive statistical analysis integrated spatial statistics, logistic regression modeling, and multivariate data integration to quantify the effects of planter and component configurations on critical performance metrics: singulation error rates, seed depth uniformity, in-row plant spacing variability, seedling emergence probability, and achieved population percentages. The results indicated that increased planting speeds generally correlated with decreased early emergence probability, particularly when utilized with specific closing devices such as spiked rubber wheels. Conversely, the adaptive dual hydraulic force control system exhibited significant potential in dynamically modulating force application in response to soil spatial variability, thereby markedly improving the consistency of seedling emergence and corn population uniformity. The integrated findings elucidate several key insights: (1) the synergistic interplay between planter speed, hydraulic downforce, and row unit location on seed placement accuracy and seedling emergence uniformity; (2) the modulation of seedling emergence rates by environmental factors and planting speed, in conjunction with closing wheel design; (3) the critical influence of closing wheel design on seed placement precision and in-row plant spacing uniformity; and (4) the promising efficacy of prototype dual hydraulic force control systems in enhancing plant stand uniformity through real-time adjustments based on prevailing soil conditions. Collectively, this research advances the understanding of how integrated mechanical configurations and operational strategies of planters can be optimized to ensure consistent corn stand establishment, ultimately leading to improved yield stability and sustainability in precision agriculture. The outcomes provide valuable guidance for the development of precision planting technologies and agronomic best practices, emphasizing the significance of engineering innovation in bolstering efficient and resilient crop production.

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Approved by:

Major Professor
Ajay Sharda

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Abstract

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To my children, Federica and Lorenzo, thank you for your unconditional love. Whenever I see you, it feels like we have never been apart; you light up my life.

Thanks to my beloved Jessica, whose smile and love hold our home together and sustain me through all challenges. I love you, my Moon.

Finally, heartfelt thanks to Bubs, Leo, and Sky, who patiently await my return at home.

Dedication

I dedicate this work to the first agricultural engineer I ever met, whom I saw walking through the cornfields, Daniel Peiretti. Thanks for everything, Dad.

And in memory of someone who had only love to give, Lucrecia. We miss you every day Mom.

Preface

This doctoral dissertation represents the culmination of several years of intensive research and dedication within the Department of Biological and Agricultural Engineering at Kansas State University. My academic journey and professional passion have been deeply rooted in advancing technologies that improve crop establishment and resource use efficiency, which are crucial challenges in contemporary agriculture. This research's focus on the multifactor evaluation of planter operational settings, hydraulic force control, and component design for enhancing corn stand establishment in precision agriculture reflects both a practical need in the agricultural industry and a scientific opportunity to integrate engineering innovation with agronomic practice. Precision planting technologies promise significant gains in sustainability and productivity, yet substantial variability in seed placement and emergence remains an obstacle that this work strives to address. This accomplishment would not have been possible without the invaluable support and guidance of my major advisor, committee members, colleagues, and family. Their encouragement, expertise, and collaborative spirit enriched every stage of this endeavor. I am especially grateful to Kansas State University and the Biological and Agricultural Engineering department for providing the resources and environment conducive to high-quality research. It is my hope that the insights and contributions contained in this thesis will advance the field of precision agriculture engineering and inspire further innovations in agricultural machinery and crop management. This work marks not only a milestone in my academic development but also a commitment to contributing meaningful solutions to the challenges faced by modern agricultural systems worldwide.

Chapter 1 - General introduction

1.1 The critical role of precision planting in modern corn production systems

As global demand for corn (*Zea mays* L.) continues to rise—fueling its role as a staple food, animal feed, and bioenergy resource—farmers face increasing pressure to enhance production efficiency and sustainability. Precision agriculture offers a transformative approach to meet these challenges by optimizing resource use and maximizing yields in a site-specific manner. Central to this approach is precision planting, which involves controlling seed placement in the soil to promote optimal germination, uniform emergence, and effective plant development (Chavas & Mitchell, 2018; Mosheim & Schimmelpfennig, 2021). Corn benefits uniquely from precision planting technologies due to its large seed size, which enables highly accurate electronic seed monitoring and control systems. Innovations such as optical seed sensors achieve counting accuracy above 96% (Nardon & Botta, 2022), while mechatronic drive systems maintain planting precision at speeds up to 12 km h^{-1}, improving seed singulation quality and reducing seed skips compared to conventional mechanical planters (Li et al., 2015). But what exactly should be the main objective of the precision planting concept? It's all about three core elements: how deep seeds are planted (vertical placement in the row), how spaced out they are in the row (horizontal placement along the row), and the quality of seed-to-soil contact achieved after placement. Correct seed depth ensures seed placement in soil microzones with optimal moisture and temperature, vital for early growth, while even spacing mitigates intra-plant competition and suppresses weeds, thereby improving resource efficiency (Maddonni et al., 2006; Toler et al., 1999). Beyond these placement parameters, adequate seed-to-soil contact—achieved through proper soil covering and compaction by closing wheels—is equally critical for precision planting success. Inadequate furrow closure or poor seed coverage can create air gaps around seeds, limiting moisture availability and thermal conductivity, thereby delaying or impairing germination even when depth and spacing are optimal (Drewry et al., 2020, 2021) Beyond hardware improvements, current planters incorporate individual row unit metering, electro-hydraulic downforce regulation, and GPS-guided section control, allowing site-adaptive planting adjusted to soil heterogeneity, residue levels, and topography (Badua & Sharda, 2023; Poncet et al., 2018; Virk et al., 2021). However, despite these advancements, maintaining consistent seed placement precision remains challenging due to planter speed, mechanical vibration, soil resistance, and variable environmental conditions (Badua et al., 2021; Poncet et al., 2019). Apparent electrical conductivity, often mapped in precision agriculture, serves as a reliable indicator of soil texture and compaction (Johnson et al., 2001; Mertens et al., 2008), aiding in the understanding of site-specific constraints on placement precision (Badua et al., 2024; Badua & Sharda, 2023). Accelerating planting speed, a desirable operational goal, often compromises precision due to increased mechanical disturbances and limitations in force responsiveness. Additionally, many conventional electro-hydraulic downforce systems apply force only unidirectionally, limiting their adaptability to spatially heterogeneous soils. Emerging dual hydraulic force control systems, capable of dynamically modulating both downforce and uplift, hold promise to overcome these limitations, though further agronomic evaluation is needed to confirm their efficacy. Understanding and optimizing the interaction between technological capabilities, planter operational dynamics, and soil variability is crucial to advancing planter design and management protocols. This integrated approach is key to achieving uniform emergence, maximizing corn yield potential, and supporting sustainable production under modern precision agriculture paradigms.

1.2 Influence of planter speed, downforce, and row unit mechanisms on seed depth and closing performance

Getting the planting depth just right is essential for ensuring that crops thrive. Research from southeast Kansas and central Missouri shows that for corn, the ideal planting depth is typically between about 38 to 51 mm with suitable moisture and temperature conditions, to 76 mm on alluvial soils, according to (Sassenrath et al., 2020; Stewart et al., 2021). If seeds are planted too shallow, they might not get enough moisture or face temperature swings, which can lead to problems like poor root growth and irregular sprouting. On the other hand, if seeds are buried too deep, it can take longer for them to sprout, and the seedlings will use more energy just trying to break through the soil (Figure 1.1), which can lead to uneven growth and lower yields. One of the main factors that affect how well we achieve the right planting depth is the downforce of the planter—the pressure it applies to create and close the seed trench without compacting the soil too much. However, maintaining consistency is challenging due to soil heterogeneity and the presence of plant residue on the surface. Additionally, parts of the planter, like closing wheels and gauge wheels, can also influence how well we manage downforce, which impacts things like soil coverage, moisture levels, and the environment immediately around the seeds. As precision planting technology gets better, it's essential to understand how all these different parts work together, how they react to different conditions, and how to adjust them. This knowledge can help ensure that we plant at the right depth, which in turn can lead to better and more uniform crop emergence and ultimately improve corn yields while boosting sustainability.

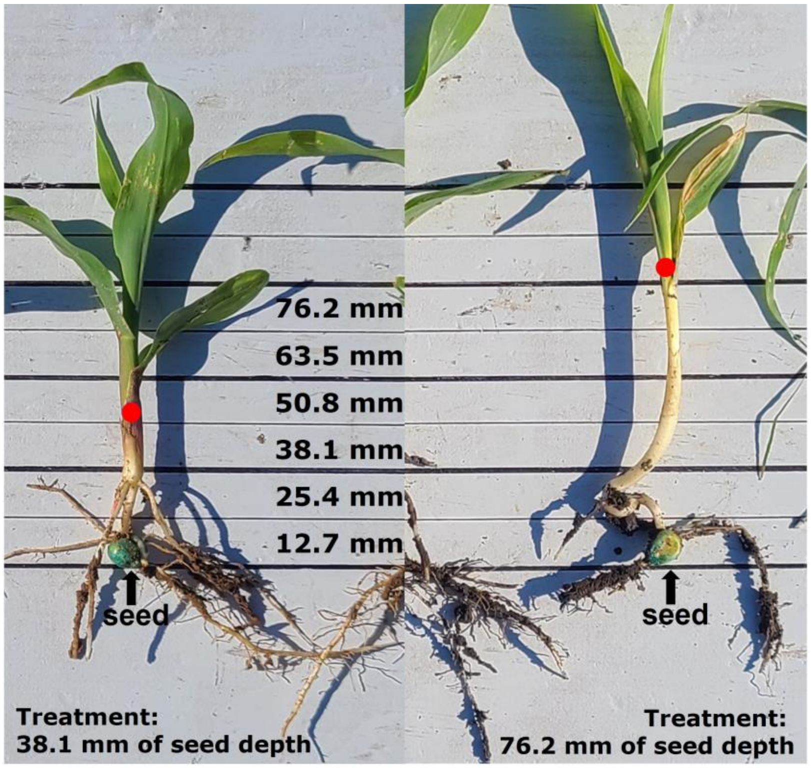

Figure 1.1. Comparative development of the corn seedling mesocotyl under two seed depths, 38.1 mm (left) and 76.2 mm (right), on the same sowing day, in the same plot, with the same planter, and using seeds of the same hybrid (DKC 65-95RIB). The red dot indicates the soil surface where the coleoptile of each seedling emerged.

Operational planter speed is a key factor affecting field efficiency and seeding precision. While higher planting speeds increase the area covered per unit time, improving operational efficiency during narrow planting windows, these speeds often reduce seed placement accuracy by increasing mechanical vibrations and bounce, negatively impacting seed depth consistency and in-row spacing uniformity (Badua et al., 2021). This diminished precision results in greater seed spacing variability, more occurrences of skips and doubles, and ultimately, increased variability in seedling emergence and overall stand uniformity. Alongside speed, the dynamic behavior of row units—including vertical acceleration and soil engagement—critically influences the quality of seed trench formation and seed-to-soil contact. Proper adjustment of gauge wheel load ensures adequate soil penetration while limiting soil compaction, both essential for creating an optimal seedbed.

Closing wheels play a vital role in covering seeds and consolidating soil over the seed furrow, affecting moisture retention and temperature stability in the seed zone, which strongly influence germination and early growth. Various closing wheel designs (Figure 1.2) have been developed to address different soil and residue conditions. Traditional rubber wheels (Figure 1.2a) provide uniform soil compaction and consistent seed coverage under conventional tillage systems, but may struggle with soil adhesion in wet conditions and can cause sidewall compaction that restricts root development. Cast iron or steel wheels (Figure 1.2c, d, e) offer greater durability and weight for improved soil firming, yet they are more prone to soil compaction and may lack the flexibility needed to adapt to varying field conditions and residue levels. Spiked or star-tooth geometries (Figure 1.2b, e) have shown promise in enhancing soil coverage and residue penetration, particularly under no-till or high-residue conditions, as their aggressive design breaks up sidewall compaction and improves soil-to-seed contact; however, they may be less effective in loose or sandy soils where excessive disturbance can reduce seed zone stability. Finger- or spring-loaded closing wheels (Figure 1.2e) provide gentle seed coverage with minimal compaction, making them suitable for delicate seedbeds, though they may not provide sufficient firming in heavy clay soils or adequate residue management in high-residue environments. The selection of appropriate closing wheel design must therefore consider soil texture, moisture conditions, tillage system, and residue load to optimize seedbed conditions for successful crop establishment (Drewry et al., 2021). Additionally, emerging technologies such as active hydraulic force control and dual-force regulation systems enable real-time modulation of downforce and uplift on row units, stabilizing planter-soil interaction in highly variable field environments. However, despite their potential benefits, these advanced systems are still insufficiently studied in operational settings with rapid planter speed variation and spatial heterogeneity. A thorough understanding of the interplay among planter speed, row unit dynamics, and closing device design is critical for optimizing seeding precision and stand establishment, ensuring maximum productivity and resource use efficiency in maize production.

Figure 1.2. Examples of closing wheel designs available in the American Midwest market during 2025 include: a) round rubber closing wheel (Deere & Company, Moline, IL); b) Twisted Spikes wheels (Yetter Farm Equipment, Colchester, IL); c) Furrow Max™ closing system (Yetter Farm Equipment, Colchester, IL); d) FurrowForce® closing system (Precision Planting, Tremont, IL); and e) Curvetine® (Surepoint, Atwood, KS).

1.3 Justification and problem statement

Existing research is frequently limited to isolated, factor-by-factor assessments, such as evaluating only planting speed or downforce. However, field conditions demand a systems-level approach that integrates interactions among planter mechanics, environmental variability, and operational adjustments. A lack of empirical data concerns dual hydraulic control systems, the combined influence of speed and closing wheel design, and the collective effects of planter system parameters on seed placement, emergence, and yield.

Despite ongoing technological advancements, a comprehensive and integrative understanding of how planter configuration variables—such as dual hydraulic force control, gauge wheel load, and row unit design—interact with spatially variable field conditions to influence planting precision and stand establishment is still missing. Most previous studies have overlooked the multifactorial and interactive nature of these relationships, particularly under the heterogeneous field environments typical of the U.S. Midwest

1.4 Research objectives

1.4.1 General objective

To systematically evaluate, at the field scale, the multifactorial effects of advanced planter operational variables—including dual hydraulic force control, planting speed, and row unit design—on the accuracy of seed placement, emergence uniformity, and stand population outcomes for maize production in a precision agriculture context.

1.4.2 Specific objectives

a. To evaluate the combined effects of hydraulic downforce magnitude and planting speed on seed depth uniformity, emergence rate, and in-row plant spacing, specifically considering spatial variability among individual row units within a planter toolbar.

b. To assess the influence of planter operating speed and closing wheel design configurations on early seedling emergence probability and uniformity, accounting for variations in soil temperature and moisture conditions.

c. To determine how different closing wheel systems and planting speed affect seed placement accuracy, plant spacing uniformity, and final plant population, incorporating the effects of heterogeneous soil environments.

d. To investigate the agronomic and mechanical benefits of dual hydraulic force regulation on row unit dynamics, seedbed conditions, and stand establishment in precision planting, emphasizing adaptive responses to spatial soil variability and operational parameters.

Chapter 2 - Combined effects of planter speed, downforce setting, and row unit location over corn seed placement[1]

2.1 Abstract

Previous studies have added to our knowledge of the impact of planter downforce and planting speed on corn seed placement. However, some unanswered questions remain regarding seed position consistency like the influence of the row unit location on the toolbar and the optimal selection of downforce margin and planting speed to ensure the optimal establishment of the crop. This study investigates the influence of downforce margin, planter speed, and toolbar row unit location on corn seed placement accuracy. Corn was sowed using a John Deere planter with "ExactEmerge" Row units and individual row hydraulic downforce control. An experimental design in a split-split RCB design with three repetitions was used. Within each experimental unit, four treatments of downforce margin were applied: 441, 775, 1108, and 1442 N, three planting speeds: 8, 12, and 16 km/h, and three planter toolbar sections: wing, no track, and track. After planting, 5.3 m of experimental strips were marked. Seedling emergence, seed depth, and plant spacing were assessed over 2,825 plants in the experiment. Data preparation and statistical analysis were conducted using Python modules through Jupyter Lab. The results showed that the effect of downforce on the achieved seed depth obtained a significant response in depth under the 1441 N treatment and at 8 and 12 km/h speed but that it ceased to be significant when working at 16 km/h. This effect was also reflected in the emergence of seedlings, where treatments with 441, 775, and 1108 N of downforce, which did not show significant differences in seed depth, achieved the highest percentage of early seedling

[1] This chapter was submitted for publication as a peer-reviewed research paper to the Journal of Precision Agriculture.

emergence within the first 48 hours. The findings reveal that the interaction between Downforce and Speed highly influenced the Precision index, that the Miss index and Quality of Feed index were more influenced by the interaction between Downforce and the Planter Section, and that the triple interaction between Downforce, Speed, and the Planter Section influenced the Multiple index of plant spacing more significantly. Furthermore, the findings emphasize the significance of adjusting the downforce supply in the row units distributed along the same toolbar. This adjustment ensures that seeds placed by each row unit along the entire width of the planter are at a uniform depth. This is important because there were significant differences in row unit acceleration, opening disk, and gauge wheel load (GWL) values between planter sections.

2.2 Introduction

Precision planting techniques, which entail the precise placement of seeds concerning spacing and depth, have become the primary method of seeding corn. Precision planters have long focused on improving the uniformity of corn emergence through both vertical and horizontal locations (Zhai et al., 2020). From the point of view of the vertical axis, the seed depth can affect the seedlings growth and success emergence rate (Conceição et al., 2016). On the horizontal axis, proper distribution of plants reduces competition and suppresses weeds (Zhai et al., 2020). Planting is a pivotal step in corn production that enables the ideal placement of seeds for uniform emergence, ultimately leading to maximum yield. This can only be achieved by ensuring that the seeds are placed in a favorable environment for germination and growth. In summary, to attain optimal outcomes, operators should pay close attention to two critical factors during planting: uniform seed depth and plant spacing (Badua et al. 2019; Hudspeth Jr. & Wanjura, 1970).

The optimal seed depth for corn varies depending on soil characteristics and growing seasons. Variations in soil conditions can cause non-uniformity in seed depth, affecting emergence (Poncet et al., 2018). Seeding too shallow can lead to better plant growth and emergence and too deep can cause adverse effects such as delayed emergence and poor root development (Poncet et al., 2019). This finding contradicts prior research that indicated a positive correlation between deeper seed depths and emergence rates. Nevertheless, it is plausible that this discrepancy is attributable to augmented water availability and soil temperatures during nocturnal hours (Knappenberger & Köller, 2012). Seedling emergence variability impacts yield more than plant spacing variability (W. Liu et al., 2004b). Adjusting planting depth can improve crop performance and yield, although the correlation between emergence date and yield may vary based on soil type (Kimmelshue et al., 2022a; Nemergut et al., 2021).

Experts found that using a single depth and downforce setting can make it challenging to achieve the desired seed depth for corn in fields with varying conditions. The final seed depth tended to be deeper than the shallower target seed depth treatment but shallower than the deeper target seed depth treatment, regardless of soil diversity (Virk et al., 2020). Choosing the proper planting downforce is crucial for maximizing soil potential and minimizing soil compaction. Increasing row unit downforce decreases plant population and increases soil resistance (Poncet et al., 2019). However, the optimal range of downforce depends on soil conditions and target seed depths. The amount of downforce impacts the depth quality index, which comprises the number of depth readings out of the total within a range of ± 10 mm around the target depth (Poncet et al., 2019). Higher soil compaction leads to less accurate seed depth, as shown by the increase in variation coefficient from 9.20% to 12.04% when soil compaction increased from 273.8 kPa to

730.1 kPa. Choosing the proper downforce can improve seed planting in varying soil conditions and depths (Zhao et al., 2019). Tractor traffic significantly influences planter penetration, primarily through its impact on soil compaction, reducing soil porosity, and increasing soil resistance (Elaoud & Chehaibi, 2011; Young & Voorhees, 1982). This compaction can be further influenced by tractor design and soil parameters (Botta et al., 2012). Tractor traffic can lead to spatial variability in soil strength and water content, affecting planter penetration into the ground (Ferrero et al., 2005). Therefore, it is essential to consider the potential adverse effects of tractor traffic on soil compaction and planter penetration to better understand the planter's task. The results of experiments using two 16 row unit planters showed that the seed depth accuracy was over three times better when 978 N of downforce was applied, compared to 533 N of downforce, for row units operating between the tractor tracks. The interaction effect between row location over the planter toolbar and downforce treatment significantly impacted emergence speed and plant spacing (Mishler, 2021).

Several studies have highlighted the impact of planting speed on stand uniformity. It has been observed that faster speeds can lead to increased variability (W. Liu et al., 2004b; Staggenborg et al., 2004). Furthermore, higher planting speeds may potentially result in decreased plant population and increased variability (Lauer & Rankin, 2004; Nielsen, 1995). In a recent study, it was found that different travel speeds significantly affected seed spacing uniformity with the air-pressure type seed meter was shown to perform the best in achieving uniformity (Q. W. Liu et al., 2017). Vertical vibration during planting can impede seed metering and delivery, causing planting variability. Row unit vibration increases with planting speed and can lead to spatial variability in planting (Badua S. et al. 2021; Hanna et al. 2010; Zhai et al.

2020). Seed depth and plant spacing can be compromised if operational speed exceeds a certain threshold (Zhao et al., 2019).

While previous studies have improved our understanding of how downforce and ground speed affect corn seed placement, they have also raised additional questions requiring further research. Hence, the objectives of this study are: i) to assess the impact of varying downforce and speed settings on seedling emergence speed, plant spacing, and seed depth; and ii) To determine whether the location of the row unit in the planter's various sections significantly affects its recorded values of acceleration, opening disk load, and GWL, and whether these differences influence crop planting parameters.

2.3 Materials and methods

2.3.1 Field description

The experiment was conducted in Clay Center, Kansas, (39.35ºN, 97.18ºW) during the 2023 planting season. The total area of the selected field was 85.32 hectares, with 12.29 hectares planted with the experimental treatments (Figure 2.1). No-till farming techniques and a pivot irrigation system were used to manage the field, with a crop rotation cycle of soybeans (*Glycine max L.*) and corn beginning Spring 2020. Table 2.1 shows weather conditions 72 hours before planting on April 24, 2023 (Kansas State University, 2023).

Table 2.1. Weather conditions in the 72 hours before planting (April 24, 2023) at Clay Center, Kansas (39.35°N, 97.18°W). Variables measured: air temperature (max/min), relative humidity (RH), precipitation (PRCP), wind speed (avg/max), soil temperature at 2" and 4" depths (max/min), and total daily solar radiation (SR). No precipitation was recorded during this period.

Date	Air temp.		RH[a]	PRCP[b]	Wind speed		2” depth soil temp.		4” depth soil temp.		SR[c]
	max ºC	min ºC	avg %	mm	avg m/s	max m/s	max ºC	min ºC	max ºC	min ºC	Total MJ/m^2
04/21/2023	13.3	1.9	52.1	0	4.0	12.3	16.7	9.8	14.4	10.4	26.4
04/22/2023	11.2	-0.8	51.2	0	3.9	11.8	17.5	7.5	14.6	8.5	26.8
04/23/2023	15.1	-3.0	47.5	0	1.3	6.5	19.4	7.1	15.8	8.0	26.0

04/24/2023	18.0	3.8	47.3	0	3.9	11.5	17.1	9.6	14.5	9.9	20.7

[a]RH: relative humidity; [b]PRCP: precipitation; [c]SR: solar radiation.

Soil apparent electrical conductivity (ECa) was collected using an ECa sensor (DUALEM, Milton, Ontario) mounted on a John Deere utility vehicle (Deere & Company, Moline, IL). A soil ECa map was then generated using ArcGIS Pro (ESRI, Redlands, CA), delineating the field into three different soil ECa zones and determining the placement of experimental units (EU) across the field (Figure 2.1).

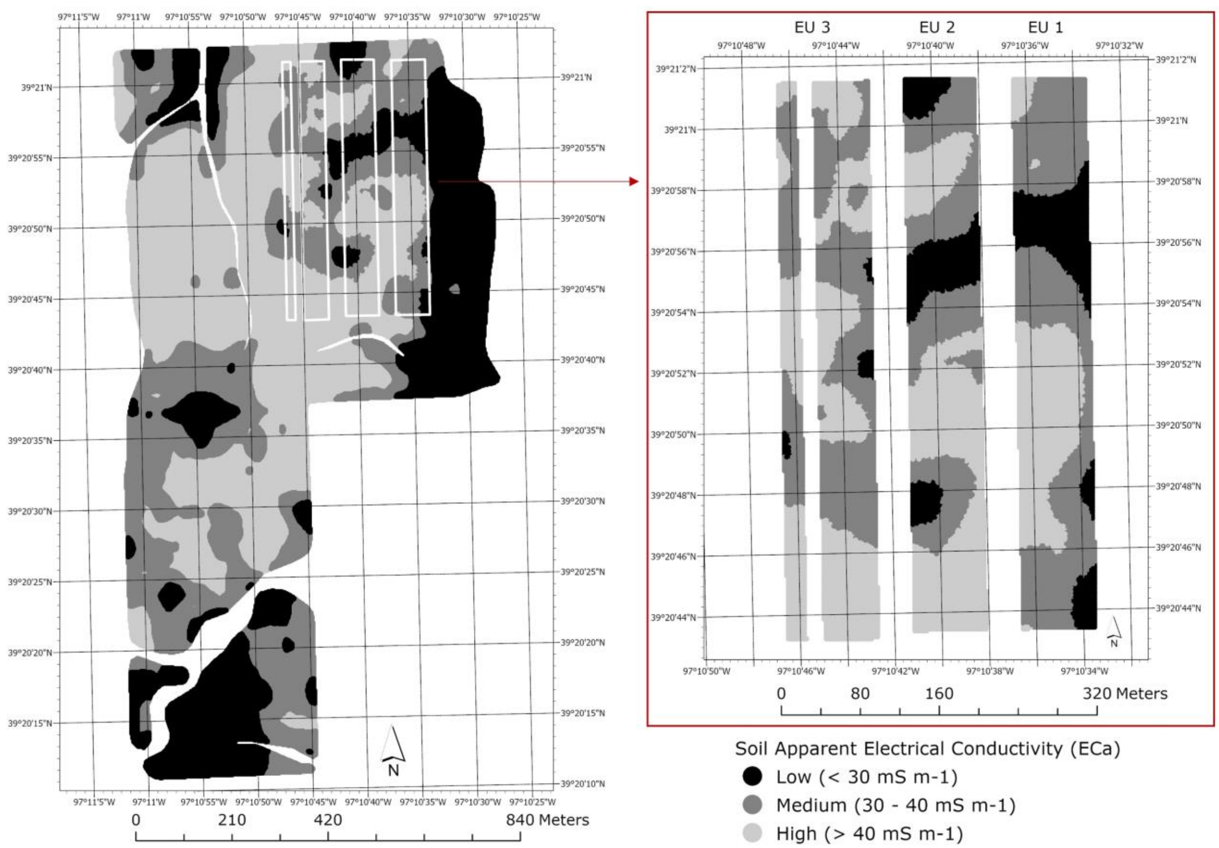

Figure 2.1. Soil apparent electrical conductivity (ECa) map at 50 cm depth for the experimental field in Clay Center, Kansas (left panel), with detailed view of the three experimental units (EU 1-3) used in the study (right panel). ECa values were classified into three categories: Low (< 30 mS m⁻¹, dark gray), Medium (30-40 mS m⁻¹, medium gray), and High (> 40 mS m⁻¹, light gray), representing soil spatial variability in texture, moisture retention, and salinity. Each experimental unit spans the full width of the planter (24 row units) and encompasses the range of soil conductivity zones present in the field.

On the planting day, nine soil samples were collected from the field at a depth of 305 mm using a Classic Soil Probe soil sampler (Oakfield Apparatus, Fond du Lac, WI) with a 19 mm inner probe diameter. Samples were collected systematically to ensure even collection across the field. The collected samples were subsequently sent to the Soil Testing Laboratory at Kansas State University for soil textural analysis. Texture results showed that the experiment terrain consisted of silty-clay-loam soil types with averages of 57.67% clay, 30.22% silt, 12.11% sand, and 24.93% moisture content. Soil taxonomy conformation in the experiment area was 55.1% Crete silt loam, 0.5% Crete silty clay loam, and 44.4% Geary silt loam (USDA et al., 2025).

2.3.2 Equipment setup and instrumentation

Field planting was made with a John Deere 1775 NT 24row30 planter with 24 row units spaced 762 mm apart (Figure 2.2), operated by a John Deere 8R 410 tractor and controlled using a SeedStar™ 4HP planting monitor (Deere & Company, Moline, IL). This equipment used ExactEmerge™ row units, which included a BrushBelt™ trench delivery system to transport seeds from the meter into the furrow. Each row unit had an electric drive metering system to ensure accurate seed delivery. During the experiment, active individual downforce hydraulic control was set up in each row unit. Each row unit was calibrated to the target planting depth of 50.8 mm using a calibration tool (Set-N-Seed, Oakdale, IL). Talc 80/20 graphite seed flow lubricant (Talc USA, Curran, IL) was used at 38 grams per 80,000 seeds in all field plantings. The row cleaners were adjusted to approximately 240 kPa, and the closing wheels were set in the "C" position, which was deemed suitable for the conditions of the field examined.

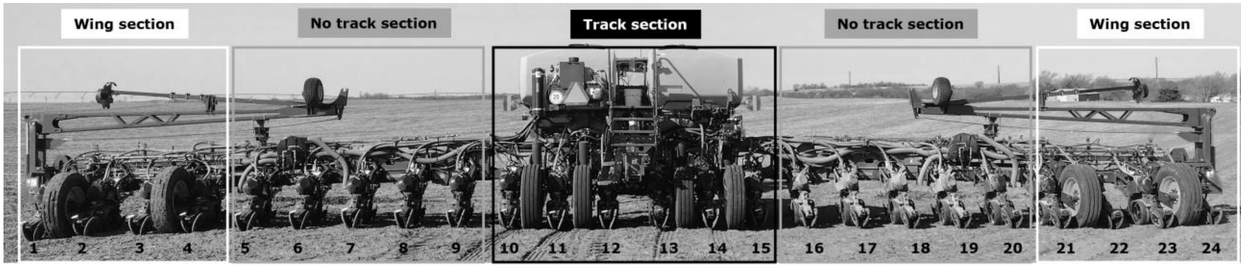

Figure 2.2. John Deere 1775 NT 24-row planter used in the experiment, showing the classification of row units into three sections based on their operational position over the planter's toolbar. Wing section (row units 1-4, 21-24) operates at the toolbar extremes; No-track section (row units 5-9, 16-20) operates outside wheel tracks in uncompacted soil; Track section (row units 10-15, highlighted with black border) operates within wheel tracks compaction range created by the tractor during planting. This sectional classification allows for assessment of how soil compaction from wheel traffic affects planter performance and post-planting metrics.

A custom-made data acquisition system was developed to monitor and log real-time planting parameters. Only the odd-numbered row units (12 out of 24) of the planter were equipped with a hydraulic pressure transducer model HAD 846K-A-5000-000 (HYDAC, Glendale Heights, IL) to measure the real-time hydraulic oil pressure applied. Hydraulic oil pressure readings were utilized to deduce the actual real-time downforce used by the hydraulic system on row units to implement the desired GWL target during planting. These row units were mounted with accelerometers Model 3741E1210G (PCB piezotronics, Depew, NY) to measure the vertical acceleration of the row units during planting. Location and travel speed were measured using a sub-inch accuracy GPS unit GR5 (Topcon Positioning Systems Inc., Livermore, CA). The same row units were also equipped with proprietary loadcells factory installed, which measured the real-time GWL during planting. Load cells, hydraulic pressure transducers, accelerometers, and GPS signals were recorded using a custom-made LabVIEW (National Instruments, Austin, TX) program through a control laptop computer model Latitude 3400 (Dell, Round Rock, TX) and a NI cRIO chassis via C Series modules (National Instruments, Austin, TX) at 10 Hz sampling frequency (Figure 2.3).

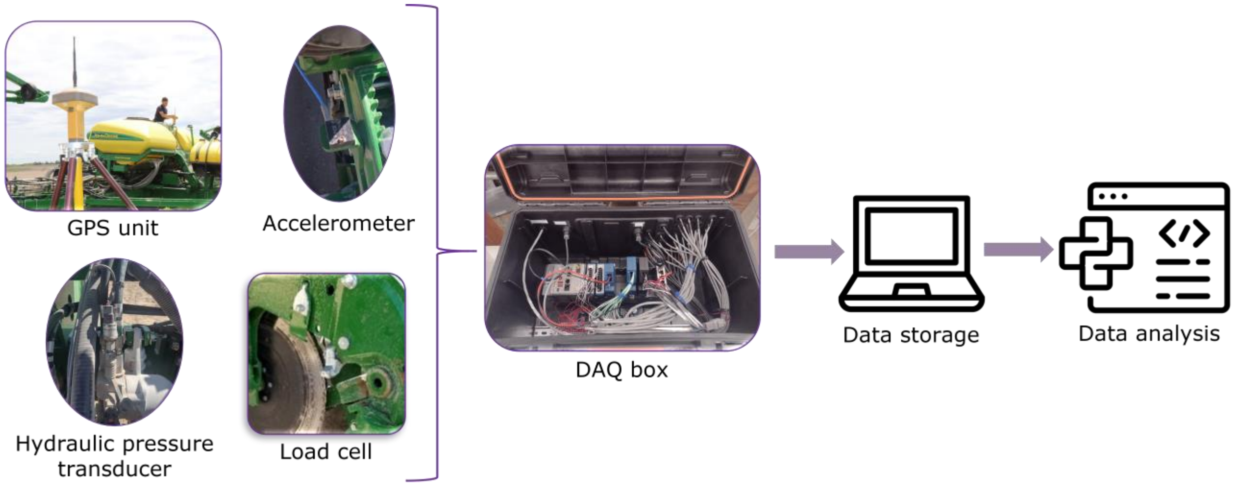

Figure 2.3. Schematic of the custom data acquisition system for collecting site-specific planter performance data. Twelve odd-numbered row units were instrumented with: GPS unit (position/speed), triaxial accelerometers (row unit motion), hydraulic pressure transducers (applied downforce), and load cells (soil reaction forces). All sensors connected to a central DAQ box for synchronized data collection at 10 Hz. Data were stored and analyzed using a custom Python code.

2.3.3 Crop agronomic management

Corn hybrid seed 214-78DGVT2 PRIB CHANNEL BIO was planted on April 24, 2023, using a seeding target of 67,954 seeds/ha in the experimental area. Ammonium Polyphosphate (10 – 34 – 0) solution was applied in-furrow at a dose of 32.27 l/ha during planting using the planter's integrated fertilizer delivery system.

2.3.4 Experiment design

The experiment was arranged in a split-split plot with a randomized design. Treatments were randomly assigned across the entire field area. Each experimental unit (EU) consisted of four side-by-side planter runs spanning 73.15 meters in width and 563 meters in length, covering an area of approximately 4.11 hectares per EU. This arrangement minimizes the influence of local temperature and moisture variations on differences in seedling emergence among treatments. The direction of the planter's runs was alternated as follows in an East-West direction in the field: North-South (1st run), South-North (2nd run), North-South (3rd run), and South-North (4th run), respecting the same order within each EU of the study. To avoid the irrigation system at the center of the field, the third and fourth runs of EU 3 needed to be separated by a distance of 18.28 meters (Figure 2.1). Four different downforce margin treatments were applied inside each EU, like the first level prediction factor: 441, 775, 1108, and 1442 N. Three planter speed treatments, like the second level prediction factor, 8, 12, and 16 km h-1, and three planter section treatments, like the third level prediction factor, were applied: no track, track, and wing (Mishler, 2021). A 5.33 meters long experimental strip was marked in one randomly chosen row of each planter section where emergence, depth and spacing were observed (Figure 2.4).

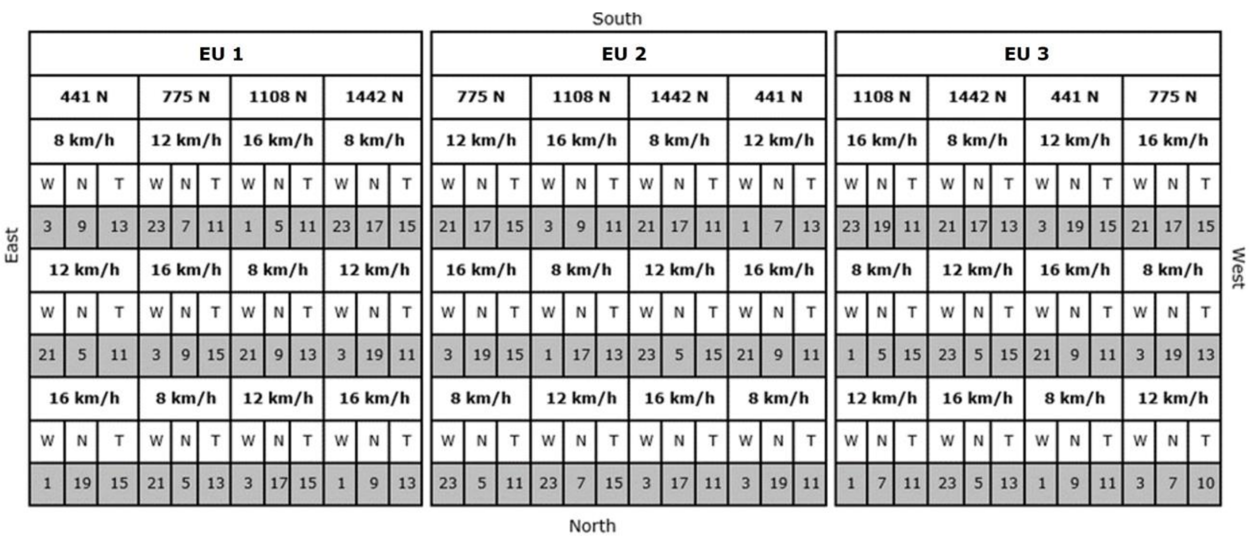

Figure 2.4. Field layout of the experiment illustrating the split-split plot with a randomized design. The three treatments—represented by letters—correspond to the planter sections: wing (W), no track (N), and track (T), respectively. Each planter section is subdivided, and within it, a row unit was randomly selected for each experimental unit, with the row unit numbers indicated in gray-shaded cells.

2.3.5 post-planting data collection

2.3.5.1 Seedling labelling and emergence

After planting, the experimental strips were visited twice daily at 8 AM and 6 PM to check for the onset and conclusion of emergence. Emergence was denoted by visually inspecting the coleoptile protruding above the soil surface inside each strip. It declared its full emergence when each strip exhibited complete emergence along its length. Any visible green points over the ground were dated and labeled using a wooden stake 10 cm long by 1 cm wide with a date/time particular code of emergence during the assessment. Once full emergence had occurred, the plant identification number was recorded, corresponding to the number of plants from the beginning to the end of the strip. This number was ascertained by noting where the planter's row unit commenced planting the strip to the final seed placed by the row unit before departing the strip according to the planter's run direction. After emergence, the last count was 2,825 corn plants labeled as the population under study within all the experimental units. It is assumed that the twice-daily visual inspections provided sufficiently accurate timing for the onset and completion of emergence, with the coleoptile visibly protruding serving as a consistent indicator. The counting method assumes that the planter's run direction and strip length delimit the planted population accurately, and that all emerged plants within the strip were detected and recorded without omission. Additionally, it is assumed that environmental and soil conditions were relatively uniform throughout each strip to avoid localized emergence variability and that no emergence occurred outside the defined strip boundaries. Limitations include the potential subjectivity of visual emergence assessment, possible missed emergence events between inspection times, and any irregularities in planting or germination not accounted for by the described method.

2.3.5.2 In-row plant spacing

In the V1 seedling state (Ciampitti et al., 2016), in-row plant spacing was measured using a standard measuring tape, Black and Decker (New Britain, CT), with a length of 7.6 m. The tape was laid out along the experimental strip, and readings were recorded for the accumulated spacing. The theoretical plant spacing (TS) of 193.2 mm was calculated based on the seeding rate and planter row unit spacing (Badua et al. 2021). The present study utilized plant spacing uniformity measurements based on the indices outlined in ISO 7256/1-1984(E) by Kachman & Smith (1995) and cited by Badua et al. (2021). These include the multiple index, miss index, quality of feed index, and precision index (referred to here as the variability index). The multiple index denotes the quantity of spacings on each experimental strip that are less than or equal to 0.5 times the TS. The miss index represents the number of spacings on each experimental unit exceeding 1.5 times the TS. The quality of feed index, or single plant, evaluates the proximity of the measured spacing to TS, by assessing the proportion of measured spacings on each experimental strip falling within the range of 0.5 to 1.5 times the TS. Finally, the variability index gauges the variability of plant spacing after accounting for skips, doubles, and singles, with lower values of this index indicating reduced spacing variability. This method assumes that the recorded plant spacings accurately reflect the actual spatial arrangement within the row, with minimal interference from plant movement or losses after emergence. It also presumes that planter operation was uniform, ensuring consistent seed delivery across treatments, and that manual measurements were sufficiently accurate despite potential effects of row curvature, uneven terrain, or operator variability. Because sampling was restricted to specific strips, it may not capture field-wide variation, and spacing indices overlook temporal shifts caused by late emergence or plant death. Although the approach provides standardized metrics for comparison, its measurement and sampling assumptions constrain the ability to fully describe spatial and temporal variability in in-row plant spacing.

2.3.5.3 Seed depth

The distance from each emerged seed's position to the soil surface was manually measured to determine seed depth at the V1 stage (Ciampitti et al., 2016). An upper reference point was established using a 2.75 millimeter thick (300 mm long and 28.18 mm wide) wooden marker positioned transversally to the planter's advance to simulate the pressure of the gauge wheels of the row unit on the surface stubble. The depth was measured using a digital caliper model SYLVAC IP67 (Malleray, Switzerland), placed perpendicular to the wooden marker with the zero mark on top. This method assumes that the wooden marker effectively represents the soil contact pressure and surface conditions of the row unit. It also relies on the assumption that the soil surface surrounding the seedlings is uniform to ensure consistent depth readings. However, differences in soil clod size, residue cover, and the accuracy of manual measurements can introduce error. Furthermore, depth assessments were limited to an early growth stage (V1), which may not reflect later changes in seed position caused by soil settling or mechanical disturbance.

2.3.6 Data analysis

The ECa mapping was conducted using ArcGIS Pro 3.13 software by Esri Inc. Datasets from the DAQ system and post-planting sampling in the experimental strips were summarized in Microsoft Excel. Subsequent statistical procedures were implemented in Python 3.11.13 using the JupyterLab interface, which facilitated interactive analysis and promoted reproducibility of results. Data wrangling and organization were handled through the "*Pandas"* package (McKinney, 2010; version 2.0.3). Inferential analyses, including pairwise comparisons with adjustments for multiple testing, were executed employing *statsmodels* (Seabold & Perktold, 2010; version 0.14.0) together with scikit-posthocs (Terpilowski, 2019), the latter specifically used for performing Tukey's honest significant difference (HSD) tests. All hypothesis evaluations adhered to a significance criterion of $\alpha = 0.05$ to maintain control of the family-wise error rate. Visualization of results was achieved using matplotlib (version 3.7.1) and seaborn (version 0.13.2), resulting in consistent, clear graphical outputs.

2.4 Results and discussion

2.4.1 Seedling emergence

The first seedling emerged 12 days after planting, which was the beginning of the experiment's emergence, which equals 135 growing degree days accumulated in the field (Patrignani et al., 2020). A Type III analysis of variance was conducted to investigate the impact of downforce, speed, and planter section on seedling emergence response expressed as the amount of time each seedling takes to emerge from the beginning of emergence (Table 2.2). The results indicated that the three-way interaction between all factors was not significant. The analysis did not reveal any significant effects for the downforce or plant section treatments when examined individually. However, the interaction between the downforce treatments and planter sections was significant at a 0.10 significance level, suggesting that downforce influenced seedling emergence time across each row unit location along the planter toolbar. Moreover, a significant interaction between downforce and speed was observed $F(1, 2812) = 4.69$, $p = 0.030$, suggesting that the impact of downforce on seedling emergence response varies depending on the speed.

Table 2.2. ANOVA results for individual seedling emergence time (hours from first seedling emergence in the experiment) as affected by downforce (4 levels: 441-1442 N), forward speed (3 levels: 8-16 km h^{-1}), and planter section (Wing, No-track, Track). Speed significantly affected emergence timing ($p = 0.0013$), with a significant downforce × speed interaction ($p = 0.0303$). * $p < 0.05$; ** $p < 0.01$.

Fixed effect	F value	p-value
Downforce	2.2	0.1315
Speed	10.3	0.0013**
PS[1]	2.2	0.1144
Downforce * Speed	4.7	0.0303*

Fixed effect	F value	p-value
Downforce * PS	2.6	0.0744
Speed * PS	1.9	0.1457
Downforce * Speed * PS	2.2	0.1112

[1] PS: planter section. [*] <0.05. [**] < 0.01.

To corroborate this, Figure 2.5 illustrates the percentage of emerged seedlings under varying downforce and planting speed conditions. The left panel (E48) shows the emergence percentage within the first 48 hours after the beginning of emergence, while the right panel (E96) displays the cumulative emergence percentage after 96 hours. Each cell in the heatmaps represents a unique combination of downforce (N) and planting speed (km h^{-1}), with the color intensity indicating the percentage of emerged seedlings. The percentage values are annotated within each cell, and red letters denote statistically significant differences between treatments according to Tukey's HSD test (alpha=0.05). The results demonstrate a significant influence of the speed treatment and its interaction with the downforce treatment on the early emergence speed of the seedlings (E48), as well as significant differences observed between each combination. In panel E96 of Figure 2.5, this influence is no longer statistically significant, suggesting that there was no differential effect of the combination of downforce and speed treatments on the seedling stand in the first 96 hours after emergence began.

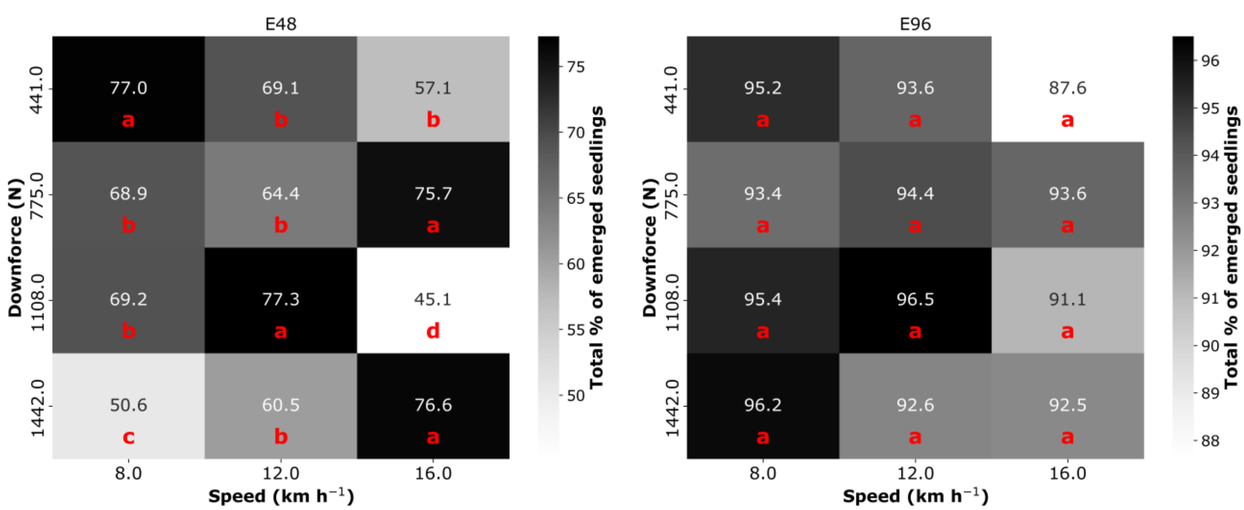

Figure 2.5. Cumulative seedling emergence expressed as percentage of total emerged seedlings at 48 (E48) and 96 (E96) hours after planting under different combinations of planter downforce (N) and forward speed (km h^{-1}) treatments. Values represent the proportion of seedlings that had emerged at each time point relative to the total number of seedlings that eventually emerged during the experiment. Darker shading indicates faster emergence rates. Different lowercase letters within each panel indicate statistically significant differences among treatment combinations (Tukey's HSD test, α = 0.05); treatments sharing the same letter are not significantly different.

These results suggest that the interaction between downforce and planter speed significantly affected the early emergence rate of corn seedlings, causing some experimental strips to have faster emergence than others. In these we observed that lighter downforce on the row units accelerated early emergence (E48) at speeds of 8 and 12 km h^{-1}.

The findings are in line with prior research, which discusses the significant influence on the appearance of emergence. This influence seems to originate from the varying depths of the seeds in the furrow, which are caused by the diverse effects of the identical load on the row unit at different speeds. In agreement with our results, was observed that a lower load led to expedited emergence in moist soils, while a higher load resulted in swifter emergence in arid soils (Hanna et al., 2010). It has been shown that seeds that are located deeper in the soil experience significant delays in the emergence of their seedlings (Kimmelshue et al., 2022b; Nemergut et al., 2021) but with a more significant number of emerged seedlings (Knappenberger & Köller, 2012). In warmer climates, emergence did not exhibit any significant variance between deeper and shallower seed depths; however, in colder climates, faster emergence was observed in shallower seed depths (Poncet et al., 2019). A study sought to ascertain the influence of compaction on seedling emergence. The findings revealed that treatments with lighter loads on the row units (530 vs 979 N) on the track section of a CASE IH Early Riser 16 row planter witnessed a 21% increase in seedling emergence (Mishler, 2021). Our results show that the emergence of seedlings during corn sowing cannot be solely attributed to the downforce exerted on the row units. The effect of this load treatment is contingent upon a combination of factors, including the machine's speed and the row unit's location within the width of the planter's toolbar. Therefore, it is imperative to consider these variables' interactive influence when evaluating seedlings' emergence in corn planting.

2.4.2 In-row plant spacing

The results from the in-row plant spacing measurements are detailed in Table 2.3, illustrating the various combinations of downforce and speed utilized in the experiment. After carrying out the multi-comparison of means (α=0.05), it was determined that there were notable disparities in the average plant spacing solely among the three speeds assessed with the 441 N load treatment on the row unit. No significant variances in plant spacing were observed between speeds in the remaining three downforce treatments. However, important distinctions were found in the average values of the multiple, miss, quality of feed, and variability indexes for the different combinations of downforce and speed.

Table 2.3. In-row plant spacing metrics by downforce and speed treatment, measured manually and calculated per ISO 7256/1-1984 standard with target spacing of 193.2 mm. Metrics: mean spacing, coefficient of variation (CV), Multiple index (< 96.6 mm), Miss index (> 289.8 mm), Quality of feed (96.6-289.8 mm), and Variability index. Different letters within columns indicate significant differences (Tukey's HSD, α = 0.05). treatments sharing the same letter are not significantly different. Higher quality of feed index and lower miss/multiple indices indicate superior planting uniformity.

Downforce (N)	Speed (km h^{-1})	Mean plant spacing (mm)	CV (%)	Multiple index (%)	Miss index (%)	Quality of feed index (%)	Variability index (%)
441	8	210.91 b	34.42	0.43 a	6.09 d	93.48 c	33.42 f
	12	205.83 a	26.37	0.85 b	5.93 c	93.22 c	15.16 a
	16	214.29 c	29.66	1.33 c	8.41 e	90.27 d	43.48 g
775	8	202.73 a	21.27	0.83 b	3.32 a	95.85 a	16.65 a
	12	205.69 a	23.75	0.43 a	5.15 b	94.42 b	25.67 c
	16	203.72 a	23.88	0.85 b	3.83 a	95.32 a	24.57 c
1108	8	202.19 a	23.01	0.83 b	4.58 a	94.58 b	26.51 c
	12	206.24 a	25.82	0.44 a	5.24 b	94.32 b	22.06 b
	16	205.41 a	27.53	2.11 d	5.91 c	91.98 c	27.62 c
1442	8	207.61 a	26.04	0.43 a	5.11 b	94.47 b	29.35 d
	12	201.84 a	22.02	0.82 b	3.29 a	95.88 a	31.65 e

16	204.79 a	22.18	0.00 a	4.18 a	95.82 a	23.97 c

The study examined the fixed effects and interactions of the row unit's downforce, planter speed, and position in the toolbar on plant spacing uniformity measurements: multiple, miss, quality of feed, and variability indexes. The calculated eta-squared (ηp2) values, presented in Table 2.4, provide insights into the differential influence of each fixed effect and interaction on the variability observed in each plant spacing uniformity measurement. The findings indicate that the row unit's combination of downforce, speed, and toolbar placement significantly impacted over the measurements. Additionally, the variability in plant spacing was primarily influenced by the interaction of downforce and planter speed.

Table 2.4. Partial eta-squared (η^2p) values quantifying the proportion of variance in in-row plant spacing quality indices explained by downforce (441, 775, 1108, 1442 N), planter fspeed (8, 12, 16 km h^{-1}), planter section (Wing, No-track, Track), and their interactions. Values represent the percentage of total variance in each spacing index attributable to each effect. Larger η^2p values indicate stronger effect sizes. The three-way interaction (downforce × speed × planter section) explained the largest proportion of variance in multiple index (43.0%), miss index (27.7%), and quality of feed index (30.8%), while the two-way interaction (downforce × speed) explained most variance in Variability index (69.2%). ns = not significant effect (p > 0.05). Spacing indices defined according to ISO 7256/1-1984 standard.

	Multiple indexes	Miss index	Quality of feed index	Variability index
Downforce	6.8	13.8	14.4	18.8
Speed	4.2	1.4	2.8	12.0
PS[1]	11.7	3.4	ns[2]	ns[2]
Downforce * Speed	15.3	6.5	7.0	69.2
Downforce * PS	10.5	37.7	33.1	ns
Speed * PS	8.5	9.5	11.6	ns
Downforce * Speed * PS	43.0	27.7	30.8	ns

[1] PS: planter section; [2] ns: not significant effect over index variability (p-value > 0.05).

These results are contradictory to other studies using a 16-row planter that found no speed or downforce margin effect on the distance between corn plants (Badua et al., 2021). In the same way, using a planter with equal toolbar width, no significant differences were found in the plant spacing across three planting speeds (9.7, 12.1, and 16.1 km h^{-1}) (Mishler, 2021). The different downforce margin treatments on the row units also did not generate significant differences in the spacing between plants in a 4-row planter (Hanna et al., 2010). On the other hand, the results found in our experiment confirm those of (Liu et al., 2004; Staggenborg et al., 2004), who highlighted the impact of planter speed on stand uniformity, with faster speeds leading to increased variability. It was also observed that there is a possibility of an increase in spacing variability when the planting speed was 11.3 km h^{-1} (Nielsen, 1995). In our study, we found similar results to those of Zhai et al. (2020). They discovered that as the speed of planting equipment increased from 4.82 to 14.4 km h^{-1}, the standard deviation of plant spacing also increased due to row unit vibration. This led to a decrease in the uniformity of planting. Additionally, they observed that higher speeds and vertical acceleration of the row unit led to a reduction in the quality of feed index and an increase in the miss index. In conclusion, our findings suggest that the row unit's precision of horizontal seed distribution was influenced by the interaction of downforce, planter speed, and row unit location on the toolbar. While our results did not demonstrate a linear pattern, they did reveal noteworthy variations in the treatment combinations following statistical analysis. This indicates that speed does not uniformly impact plant spacing across different levels of downforce and row unit positioning within the working width.

2.4.3 Seed depth

Table 2.5 shows the seed depth outcomes of the test III type analysis of variance from the experiment's dataset.

Table 2.5. Type III ANOVA for seed placement depth (mm, target = 50.8 mm) as affected by downforce (4 levels: 441-1442 N), forward speed (3 levels: 8-16 km h^{-1}), and planter section (Wing, No-track, Track). Seed depth was measured at V1 growth stage from seed center to soil surface using a digital caliper, with surface reference established by a wooden

marker simulating gauge wheel pressure (Ciampitti et al., 2016). Downforce significantly affected depth (p = 0.009), with a significant speed × section interaction (p = 0.001). ** p < 0.01.

Fixed effect	F value	p-value
Downforce	9.9	0.009**
Speed	1.9	0.178
Downforce * Speed	1.4	0.259
PS [1]	1.4	0.250
Downforce * PS	0.5	0.796
Speed * PS	6.0	0.001**
Downforce * Speed * PS	1.2	0.333

[1] PS: planter section. [**] < 0.01.

The F value was 9.85, with the p-value 0.009 for the fixed effect of downforce treatments on seed depth. These results suggested a significant relationship between the downforce level and the response of seed depth found in the field, as shown in Figure 2.6. Former evidence strongly supports that the planter's downforce setting directly affects the depth at which corn seeds are planted. Similar results were found with three different soil moisture contents (17.5%, 20.8%, and 13.9%) on three different sowing dates, found seed depths directly proportional (46 to 59 mm, 42 to 49 mm and 38 to 49 respectively) to the three load treatments applied (Low: 180 to 490 N, Medium: 490 to 890 N and High: greater than 890 N) by Hanna et al. (2010). In another study, specific soil properties generated influence on the seed depth results achieved, but within those properties, soil moisture content was not one of them (Poncet et al., 2018). In the same way, a study examining the impact of soil conditions and load treatments on row units observed a tendency to increase seed depth only in fields with 15% soil moisture, not in those with 26% moisture. However, other studies found that downforce margin treatments did not result in significant differences in seed depth in the field, with 26% soil moisture (Virk et al., 2020).

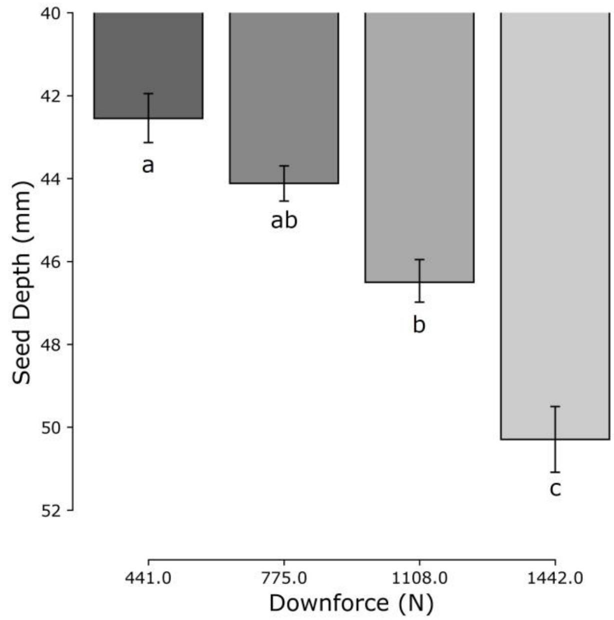

Figure 2.6. Seed depth corresponding to each downforce treatment. Results represent averages across all planter speed treatments, which were not included in this analysis. Bars represent mean values with 95% confidence intervals. Lowercase letters indicate significant differences (p<0.05).

The interaction of downforce and speed has been demonstrated by Badua et al. (2021), who reported that greater loads on the row unit were necessary to reach the target depth when working above 9.6 km h^{-1} of planter speed. In a similar experiment where the target seed depth was 30 mm, the average depth of seed placement was 28.49 mm and 25.26 mm when the speed increased from 4 to 6 km h^{-1}, respectively, according to Conceição et al. (2016). Consistent with this, a decrease in the average seed depth from 51 mm to 49 mm, with an increment of the variation coefficient of seed depth from 11.99% to 15.38%, was also detected with increases in the speed from 3 to 5 km h^{-1} (Zhao et al., 2019). This particular response was also noted by (Mishler, 2021). Although there was no difference in seed depth results between 9.7 and 12.1 km h^{-1}, the analysis indicated that the precision in depth management at these slower speeds was twice as good as the seeding depth at 16.1 km h^{-1}. Our findings did not reveal a significant impact of speed or its interaction with the downforce treatment on the seed depth response, as indicated in Table 2.5. This conclusion is supported by the observation that significant differences in seed depth means were only evident when the heaviest load (1442 N) operated at 8 and 12 km h^{-1} (Figure 2.7).

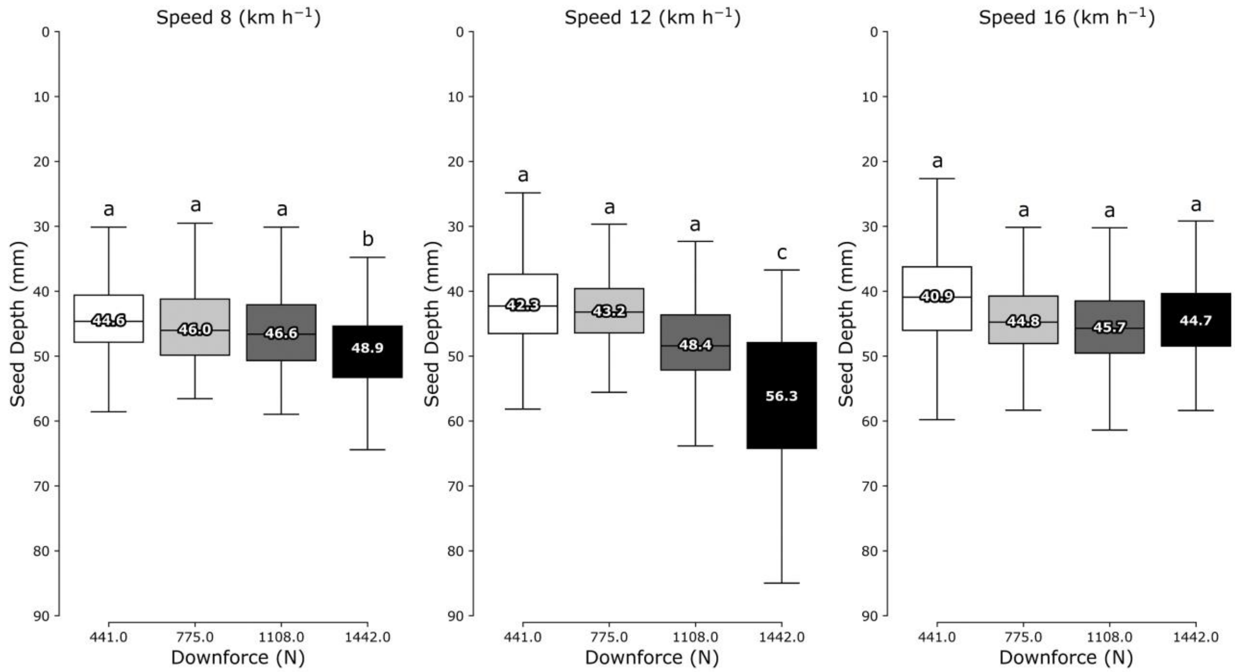

Figure 2.7. Seed depth response to downforce and speed treatments. Boxes represent the interquartile range (25th to 75th percentiles), horizontal lines within boxes indicate medians, and whiskers extend to 1.5× the interquartile range. Outliers were excluded from the plot. Lowercase letters indicate significant differences ($p<0.05$).

On the other hand, in our findings (Table 2.5), we observed a significant impact of the interaction between speed and the position of the row unit on the planter toolbar (Figure 2.8). Previous research has provided limited evidence of the effects of this interaction type on seed depth. Similar results were found by (Mishler, 2021), indicating a significant effect of the interaction between row type and downforce level on seeding depth accuracy. His analysis revealed that the seeding depth accuracy was more than three times better at 978 N of downforce compared to 533 N for track rows. However, this effect did not apply to the other row types.

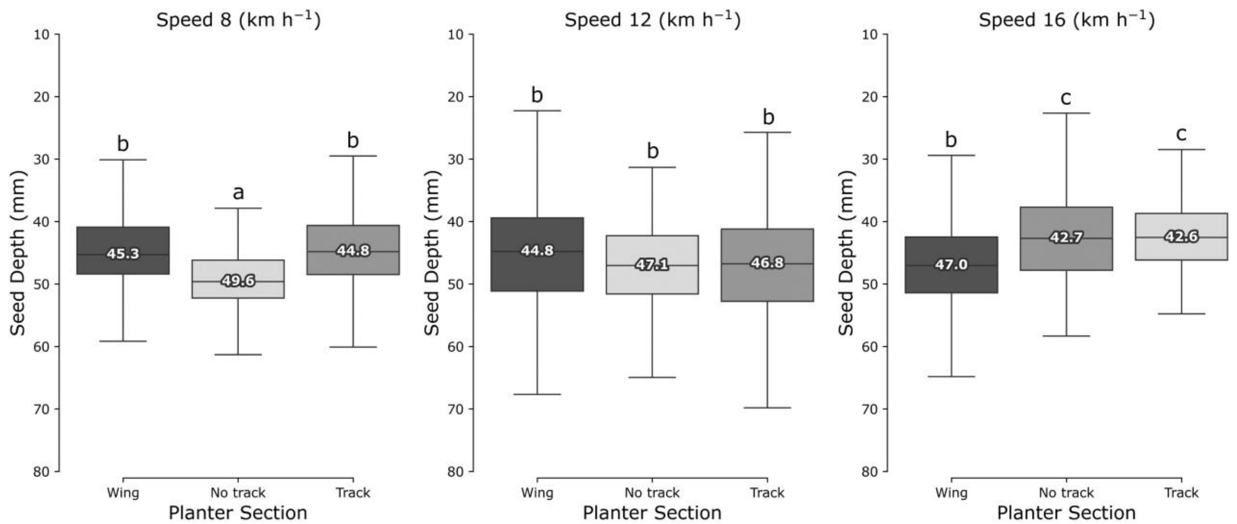

Figure 2.8. Seed depth response to planter section and speed treatments. Boxes represent the interquartile range (25th to 75th percentiles), horizontal lines within boxes indicate medians, and whiskers extend to 1.5× the interquartile range. Outliers were excluded from the plot. Lowercase letters indicate significant differences ($p<0.05$).

Our results lead us to conclude that the downforce demand will differ depending on where the row unit is positioned in the planter and that the intensity of that demand will vary with speed changes. Further studies will be necessary to fully understand this interaction between downforce, speed, and row unit position.

2.4.4 Sensing of row unit electronic data

The DAQ system collected acceleration, opening disc load (ODL), and GWL values from the odd row units of each planter's section. GWL was obtained from the proprietary load cells. ODL was obtained by integrating data from hydraulic pressure transducers, GWL, and the weight of the row units. The furrow closure system's load value was subsequently deducted. The acceleration values for the comparison between the wing vs. no track section and the track vs. no track section can be seen in Figures 2.9 and 2.10, respectively. These figures showed the reference of the downforce and speed treatments for each of the three EU of the experimental design. From observing these figures, it can be drawn that when operating under the fastest speed treatment, the planter's behavior results in higher acceleration values for all planter sections.

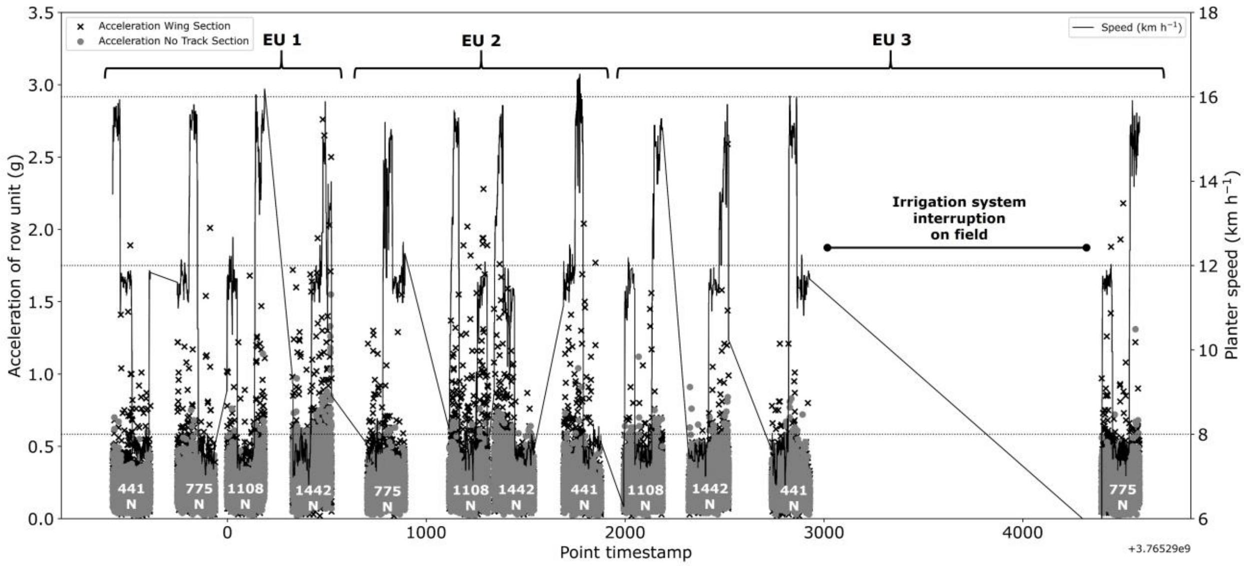

Figure 2.9. Real-time acceleration (g) of planter row units operating in the wing section (×) and the no track section (●) across three experimental units (EU). Each experimental unit combined four downforce treatments (441, 775, 1108, and 1442 N) applied at varying planter speeds (solid line, right axis). Data points represent high-frequency acceleration measurements collected sequentially along the field. Acceleration spikes correspond to increased vertical movement of the row units. Note: Irrigation system interruption occurred during data collection in EU 3, creating a timestamp gap in the plot.

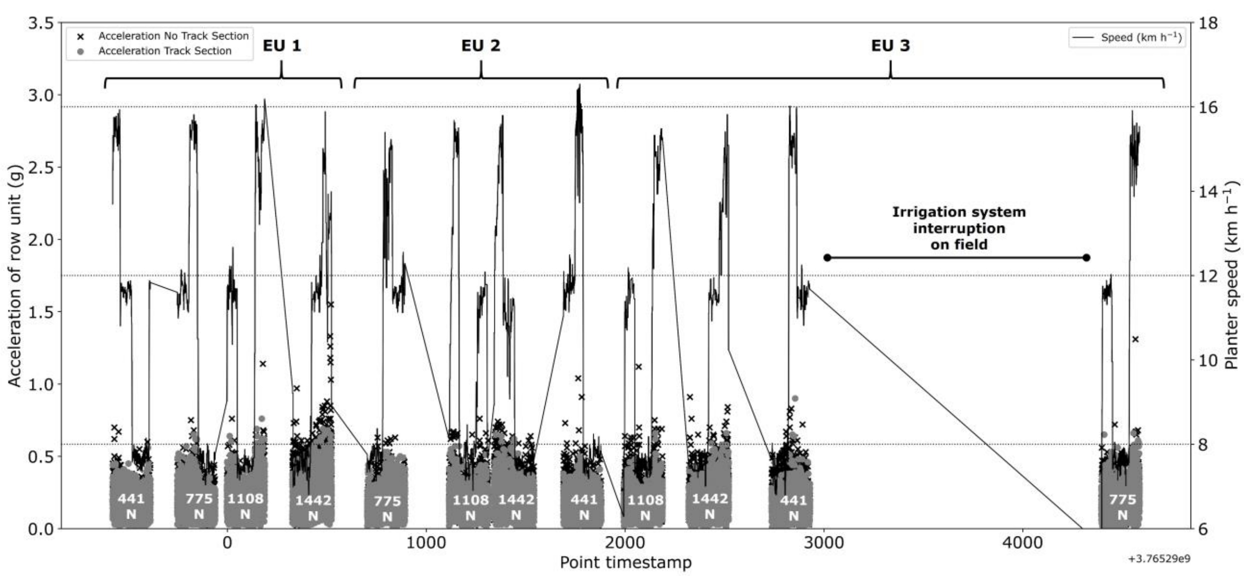

Figure 2.10. Real-time acceleration (g) of planter row units operating in the no track section (×) and the track section (●) across three experimental units (EU). Each experimental unit combined four downforce treatments (441, 775, 1108, and 1442 N) applied at varying planter speeds (solid line, right axis). Data points represent high-frequency acceleration measurements collected sequentially along the field. Acceleration spikes correspond to increased vertical movement of the row units. Note: Irrigation system interruption occurred during data collection in EU 3, creating a timestamp gap in the plot.

This corroborates the results found by Zhai et al. (2020), who found a linear increase in row unit vibration on a planter similar to the one used in this experiment. This author observed that a greater vibration of the row unit caused by the greater roughness of a No-till surface of the field causes greater row unit vibrations, even at low and medium speeds. Other researchers have also established a correlation between elevated vibration rates in the row unit and an upsurge in the velocity of the planter (Badua et al., 2021; Zhai et al., 2020; Zhao et al., 2019). They further noted that this phenomenon of the row units could be mitigated by increasing the downforce margins, which in turn could enhance seed placement accuracy in the presence of high vibrations (Badua et al., 2021).

Figure 2.9 shows higher acceleration records in the wing section's row units than in the planter's no track section. However, in Figure 2.10, the disparity between the track and no track sections is less apparent. Statistical analysis of this data (Table 2.6) revealed that the units in the track section exhibited significantly lower acceleration values than the other two sections.

Table 2.6. Mean acceleration values (g) for the three planter sections across all downforce and speed treatment combinations. Planter sections are defined by row unit position on the toolbar and their corresponding field location relative to tractor wheel tracks: Wing (row units 1-4, 21-24) = outside wheel tracks; No-track (row units 5-9, 16-20) = between wheel tracks in uncompacted soil; Track (row units 10-15) = within compacted wheel tracks. Values represent means across all experimental units and treatments. Different lowercase letters indicate statistically significant differences between sections (Tukey's HSD test, α = 0.05); sections sharing the same letter are not significantly different.

Planter Section	Acceleration (g)
Wing	0.2603 a
No Track	0.2598 a
Track	0.1801 b

Nevertheless, the lower acceleration recorded in the row units of the track section was not reflected in planting depth. Figure 2.11 shows the average seed depth across the three sections of the planter. No significant differences were observed in seed depth between the wing and no track section. On the other hand, we note that the row units in the track section resulted in significantly shallower seed depths compared to the other two sections.

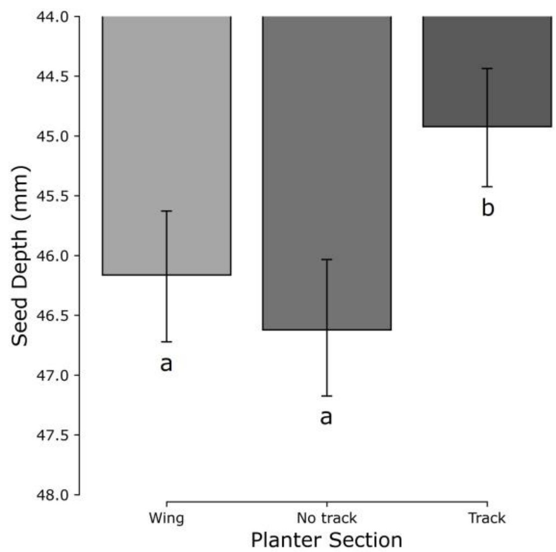

Figure 2.11. Seed depth response to row unit toolbar location treatments. Results represent averages across all planter speed and downforce treatments, which were not included in this analysis. Planter sections are defined by row unit position on the toolbar and their corresponding field location relative to tractor wheel tracks: Wing (row units 1-4, 21-24) = outside wheel tracks; No-track (row units 5-9, 16-20) = between wheel tracks in uncompacted soil; Track (row units 10-15) = within compacted wheel tracks. Bars represent mean values with 95% confidence intervals. Lowercase letters indicate significant differences ($\alpha<0.05$).

ODL in agricultural planting practices refers to the force exerted by planter discs on the soil during seeding operations. It can be quantified using real-time machine control system data and is influenced by soil conditions, with higher loads observed in heavier soils according to Badua & Sharda, (2023).

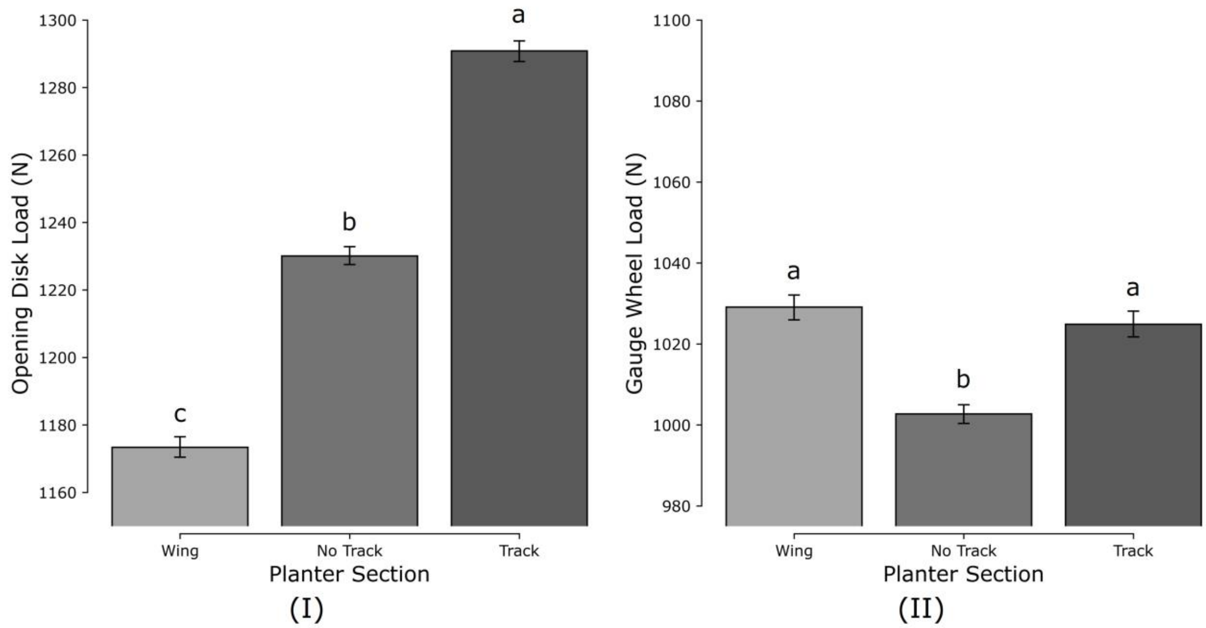

Figure 2.12. (I) opening disk load and (II) gauge wheels load response to row unit toolbar location treatments. Results represent averages across all planter speed and downforce treatments, which were not included in this analysis. Planter sections are defined by row unit position on the toolbar and their corresponding field location relative to tractor wheel tracks: Wing (row units 1-4, 21-24) = outside wheel tracks; No-track (row units 5-9, 16-20) = between wheel tracks in uncompacted soil; Track (row units 10-15) = within compacted wheel tracks. Bars represent mean values with 95% confidence intervals. Lowercase letters indicate significant differences (α<0.05).

Figure 2.12(I) indicates that the average ODL value increases from the outer row units (wing section) to the central row units (track section) of the planter. Conversely, Figure 2.12(II) reveals that GWL values are significantly higher in both the wing and track sections. The points of high and low ODL values, consistent with greater acceleration, recorded in the paths of the row units belonging to the wing section caused their average GWL values to be higher. Although none of the planter sections reached the target planting depth values, the differences between the averages were only a couple of millimeters. There were no significant differences in seed depth between the wing and non-track sections (Figure 2.11), with the latter showing a more regular behavior with higher ODL and lower GWL. Additionally, the seeding depth in the track section was shallower overall, likely due to a higher disc load and an active hydraulic downforce system. These findings align with previous research on variations in bulk density and soil penetration resistance related to tractor wheel paths (Botta et al., 2012; Elaoud & Chehaibi, 2011).

2.4.5 Discussion of uncertainty and methodological limitations

The data collected on seed depth, plant spacing, and seedling emergence provide critical insights into planter performance and early stand development. Nonetheless, several inherent sources of uncertainty and methodological limitations warrant explicit consideration. Seed depth measurements relied on the assumption that the wooden marker reliably simulated gauge wheel pressure and that soil surfaces around seedlings were uniform enough for consistent vertical measurement. Variability in surface residue, soil texture, and manual measurement precision likely introduced some error. In-row plant spacing measurements assumed that tape-based linear assessments accurately reflected the spatial distribution of seedlings at the V1 stage, with minimal post-emergence movement or mortality altering spacing. However, manual measurement accuracy, row curvature, field heterogeneity, and the restricted sampling area limited the assessment of broader spatial variability. Seedling emergence estimation depends on accurate enumeration at the declared full emergence stage, ignoring possible delayed germination or early plant mortality that affect population dynamics.

Additionally, planter operational variables, such as planter speed and downforce margin, influenced seed placement precision and emergence uniformity, contributing to the observed variability. Environmental heterogeneity across the experimental sites introduces factors beyond direct planter control, complicating causal inference. Recognizing these limitations highlights the importance of replication across conditions and the adoption of complementary sensor-based technologies to enhance reliability and confidence in future planter performance evaluations.

2.5 Conclusions

This study provided the following conclusions:

a. The interaction between downforce and planter speed significantly influenced the early emergence rate of corn seedlings. Lighter downforce led to accelerated early emergence at speeds of 8 and 12 km h^{-1}.

b. The interaction between downforce, speed, and planter section significantly affected the number of multiples and misses inside plant spacing measurements. However, downforce, speed, and their interaction significantly affected the uniformity in plant spacing only.

c. The study found that a downforce of 1441 N at speeds of 8 and 12 km^{-1} achieved significantly deeper seed depths than other downforce treatments. The shallower depth and the lack of significant differences in those obtained with the treatments between 441 and 1108 N were also reflected in the values of early seedling emergence, with a significantly higher percentage of seedlings on the surface during the first 48 hours after emergence began than in the 1441 N treatment (seeds placed deeper). However, this significance was not observed at 16 km h^{-1}. The significant effect of the heavier downforce was diluted when combined with the faster planter speed treatment (16 km h^{-1}), where there were no significant differences in seed depth with the other treatments.

d. Acceleration, opening disk, and gauge wheel load recorded for each planter section showed significant differences. This indicates that the downforce distribution should be explicitly considered for each toolbar section on the same ground point.

Using a single downforce setting for the entire planter's operation on a single field may not be sufficient to ensure consistent seed placement at all ground speeds. This is because the interaction of downforce with the position of the row unit leads to significant differences in all responses analyzed in this study. In future research, it is essential to focus on analyzing data related to the behavior of individual row units, rather than just comparing different sections. This approach will help gain a more comprehensive understanding of the variations in response to factors like downforce and speed among neighboring row units within the same toolbar.

Chapter 3 - Corn emergence rate response to planter speed and closing wheel design across different field conditions

3.1 Abstract

This study evaluated the influence of environmental conditions, planter operating speed, and closing wheel design (CWD) configurations on early corn seedling emergence and subsequent yield components. The experiment employed a split-split plot design with two planting speeds (12 and 16 km h^{-1}) and four CWD treatments, replicated across blocks. Seedling emergence and grain yield per plant were assessed, and spatial-statistical analyses were performed using ArcGIS Pro, Python, and logistic regression modeling in R to ensure reproducibility. Results demonstrate that the environment strongly modulates a faster seedling emergence rate. Increasing planting speed from 12 to 16 km h^{-1} reduced early emergence probability across all CWDs, with the most significant decline observed when combined with the SPIKES closing device. FORCE and MAX designs also significantly decreased emergence odds relative to the OEM baseline. While planter settings influence the final furrow shape—important for uniform emergence—environmental factors, especially early soil temperature and moisture availability, were the main drivers of emergence timing and individual ear dry weight. These findings highlight the necessity of integrated management strategies that align planting speed and CWD selection with site-specific environmental conditions to optimize early emergence of corn seedlings and yield potential.

3.2 Introduction

Research consistently shows that seedling emergence speed and its uniformity significantly impact corn yield, indicating a complex relationship between emergence characteristics and final crop productivity. Faster emergence and leaf appearance rates in specific genotypes can lead to earlier canopy closure and enhanced light interception, potentially benefiting yield (Begna et al., 2001). Environmental factors play a critical role in determining corn seedling emergence and subsequent crop performance. Among these, temperature is especially vital, with an optimum for corn germination estimated at around 33.6 °C (Itabari et al., 1993); both suboptimal low and excessively high temperatures can significantly hinder emergence processes (Schneider & Gupta, 1985; Weaich et al., 1996). Additionally, relative humidity and soil heat flux have also been shown to influence seedling establishment (Fayose & Fakorede, 2021). Early planting is often adopted to maximize yield potential and improve grain quality traits such as test weight and grain percentage per cob; however, it can expose seedlings to low temperature stress, impairing emergence and growth and potentially reducing both grain yield and thousand-kernel weight (Božić et al., 2025; Domokos et al., 2024; Mohsen Khudhair & Hameed Hamza, 2024). Conversely, delaying planting until early May in the American Midwest has been associated with increased yields by avoiding critical drought periods (Norwood, 2001; Staggenborg et al., 1999). Importantly, the overall impact of these climatic factors is modulated by their interactions and the specific environmental context in which corn is grown (Albuquerque & Carvalho, 2003; Dwyer et al., 2000). The speed and uniformity of emergence are paramount, as delayed emergence can reduce grain yield by 4–8% for plants emerging 2–4 leaf stages later (Dufour, 2021; W. Liu et al., 2004b). Another study found that, on average, each day of emergence delay after planting can reduce plant yield by 7%, grain number by 6%, and final crop yield by 8.5% (Albarenque et al., 2023). Uniform emergence is crucial, as delayed emergence can reduce individual ear weights due to increased interplant competition (Kimmelshue et al., 2022a; Novak & Ransom, 2018). It has been seen that uneven emergence can decrease yields by up to 2,900 kg ha^{-1} at optimal plant populations (Merotto Junior et al., 1999). In comparison, other factors like plant spacing variability have less impact on yield than emergence timing (Dufour, 2021; Liu et al., 2004b). However, the correlation between seedlings' emergence rate and grain yield is not always straightforward and depends on multiple external influences (Glenn et al., 1974). Several environmental and agronomic factors—such as soil moisture, furrow conformation, soil and air temperature, planter setup (row-unit configuration, seed depth achieved), and crop characteristics (hybrid selection and seed quality)—significantly influence emergence speed and rate (Kimmelshue et al., 2022b; Lamichhane et al., 2018; Liu et al., 2004b; Menkir & Larter, 1987). No-till systems, due to residue cover, may further exacerbate emergence variability (W. Liu et al., 2004a). Seedbed structure, including aggregate size and seed-soil contact, affects germination, emergence, and early root development (Braunack & Dexter, 1989; Lamichhane et al., 2021). Furthermore, actual seed depth correlates with seedbed moisture, roughness, and aggregate size distribution, which in turn affect germination and overall productivity (Romaneckas et al., 2022). The importance of planting equipment settings—such as planter speed and furrow closing devices —is thus underscored, as they critically affect seedbed conformation and crop establishment (Staggenborg et al., 2004). Adjustments to planter speed and the precise configuration of CWDs can influence the consistency of seed depth, soil compaction around the seed, and the degree of soil cover, all of which are pivotal for ensuring optimal microenvironmental conditions at the seed zone. The operating speed of the planter is a key factor in achieving optimal corn stand establishment and maximizing yield potential. Several studies have shown that increasing planting speed can negatively impact seedling emergence and uniformity, leading to greater variability in plant population and emergence timing (Celik et al., 2007; Liu et al., 2004a; Novak & Ransom, 2018; Staggenborg et al., 2004). This variability often results in less uniform and delayed emergence, adversely affecting early crop development and overall productivity (Liu et al., 2004a; Marques Filho & Ventura, 2021). Conversely, lower planting speeds promote stand uniformity and are associated with higher yields (Garcia et al., 2006; Marques Filho & Ventura, 2021). Consequently, planting speeds between 3 and 5 km h^{-1} are recommended to encourage uniform seedling emergence and maximize corn yield (Garcia et al., 2006; Kuş, 2021). This highlights the complexity of translating improvements in establishment into tangible yield gains and underscores the need for integrated field-scale evaluations that consider both emergence dynamics and subsequent yield components. Consequently, the objectives of this study were: i) To determine the influence of key environmental factors on the emergence rate of corn seedlings under field conditions; ii) To assess whether the emergence rate of corn seedlings significantly influences the grain yield per plant; iii) To investigate whether variations in planter working speed affect the response of corn seedling emergence rate; iv) To evaluate whether different CWD settings modify the corn seedling emergence rate; and v) To analyze whether an interaction between planter speed and CWD settings influences the corn seedling emergence rate.

3.3 Materials and methods

3.3.1 Experiment design

The experiment was conducted using a split-plot design, completely randomized within three blocks. The first-order factor consisted of two forward speed treatments, 12 km h^{-1} and 16 km h^{-1}, which were paired with four different CWD treatments, serving as the second-order factor in the experimental design.

3.3.2 Site description

The experimental design described was applied during cropping seasons 2023 and 2024, when corn was cultivated in two fields in Exeter Township, Clay County, in north-central Kansas, according to the described experimental design. The first field, Field A, was at latitude 39.239884, and longitude -97.234797. The second field, Field B, was situated at latitude 39.305457, and longitude -97.176462. The total area of Field A was 55 hectares, with 13.4 hectares planted with the experimental treatments (Figure 3.1, left). Soil taxonomy conformation in the experiment area of Field A was 48.6% Crete silt loam; 42.6% Crete silty clay loam, soil code 3802, and 8.8% Muir silt loam, according to USDA et al. (2025). The total area of Field B was 27.3 hectares, with 12.5 hectares planted with the experimental treatments (Figure 3.1, right). Soil taxonomy conformation in the experiment area of Field B was 64.3% Crete silty clay with one to three percent slopes, and 35.7% Crete silty clay loam with three to seven percent slopes, according to USDA et al. (2025). Both fields were managed as drylands employing no-till techniques. The crop rotation cycle, which began in Spring 2020, alternated between soybeans and corn.

The description of the fields using apparent soil apparent electrical conductivity (ECa) ranges denotes that the experimental area of Field A was distributed in 17.8% of the surface with < 32 (mS m^{-1}), 12.7% of the surface between 32 and 38 (mS m^{-1}), and 69.5% of the surface with between 38.0 and 45 (mS m^{-1}). In comparison (Figure 3.1), the experimental area of Field B was distributed across 1.9% of the surface with conductivity values below 32 (mS m^{-1}), 30.6% of the surface between 32 and 38 (mS m^{-1}), and 67.5% of the surface with conductivity values between 38 and 45 (mS m^{-1}).

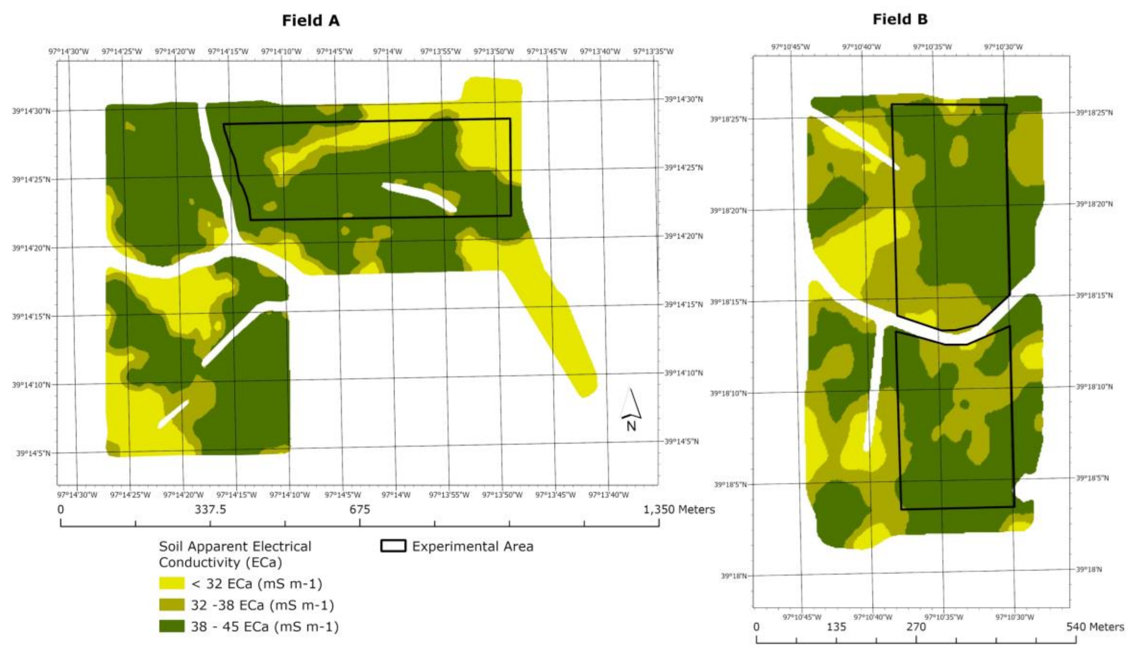

Figure 3.1. Soil apparent electrical conductivity (ECa) classification maps for experimental Fields A and B, showing three ECa zones at 50 cm depth: Low (< 32 mS m^{-1}), Medium (32-38 mS m^{-1}), and High (38-45 mS m^{-1}). Black rectangles indicate experimental areas encompassing soil spatial variability. White areas represent grassed waterways. The experiment was replicated across both fields to enhance the reliability of the results.

The daily air temperature data collected on November 10, 2025, from the Kansas Mesonet (Patrignani et al., 2020), were used to calculate cumulative corn growing degree days during the first 20 days after planting, as illustrated in Equation 3.1, where "GDD" is cumulative corn growing degree days; "DAP" is days after planting; "T_{max}" and "T_{min}" are maximum and minimum daily temperatures (°C); and "T_{base}" = 10 °C, according to Anandhi (2016).

$$GDD = \sum_{DAP=0}^{DAP=20} \left[\frac{T_{max}+T_{min}}{2} - T_{base}\right] \qquad (3.1)$$

3.3.3 Row-crop planter

Field planting was conducted using a John Deere 1775 NT 24row30 planter (Figure 3.2), featuring 24 row units spaced 762 mm apart. This setup was powered by a John Deere 8R 410 tractor and utilized a SeedStar™ 4HP planting monitor for control (Deere & Company, Moline, IL). The specific row units included ExactEmerge™ technology, equipped with a BrushBelt™ system that facilitated the transportation of seeds from the metering device into the planting furrow. Each row-unit had an electric drive metering system to guarantee precise seed delivery. Individual downforce hydraulic control was activated for each row unit throughout the experiment. The planter's row units were calibrated to achieve a target planting depth of 50.8 mm using a calibration tool (Set-N-Seed, Oakdale, IL). A graphite-based seed lubricant, Talc 80/20, was applied at 38 grams per 80,000 seeds during all field planting operations to enhance seed flow. The row cleaners were also set to a light-medium adjustment appropriate for both field conditions.

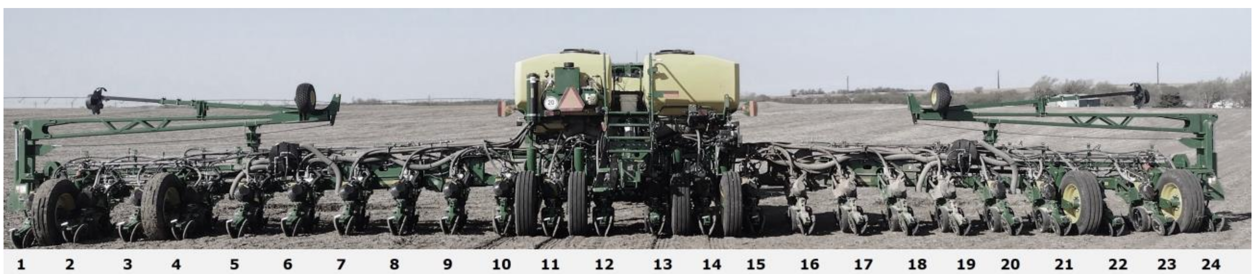

Figure 3.2. John Deere 1775 NT 24-row planter used in the experiment, with sequential numbering (1-24) for individual row unit identification and data tracking.

3.3.4 Closing wheel designs

As a second-level factor, the experiment evaluated four CWDs, one original equipment manufacturer, and three aftermarket designs for closing and covering the planting furrow as treatments. They were installed on a half-planter basis, 12 row units, randomly choosing one of the two halves of the planter to install them in the experimental planter's runs (Figure 3.3).

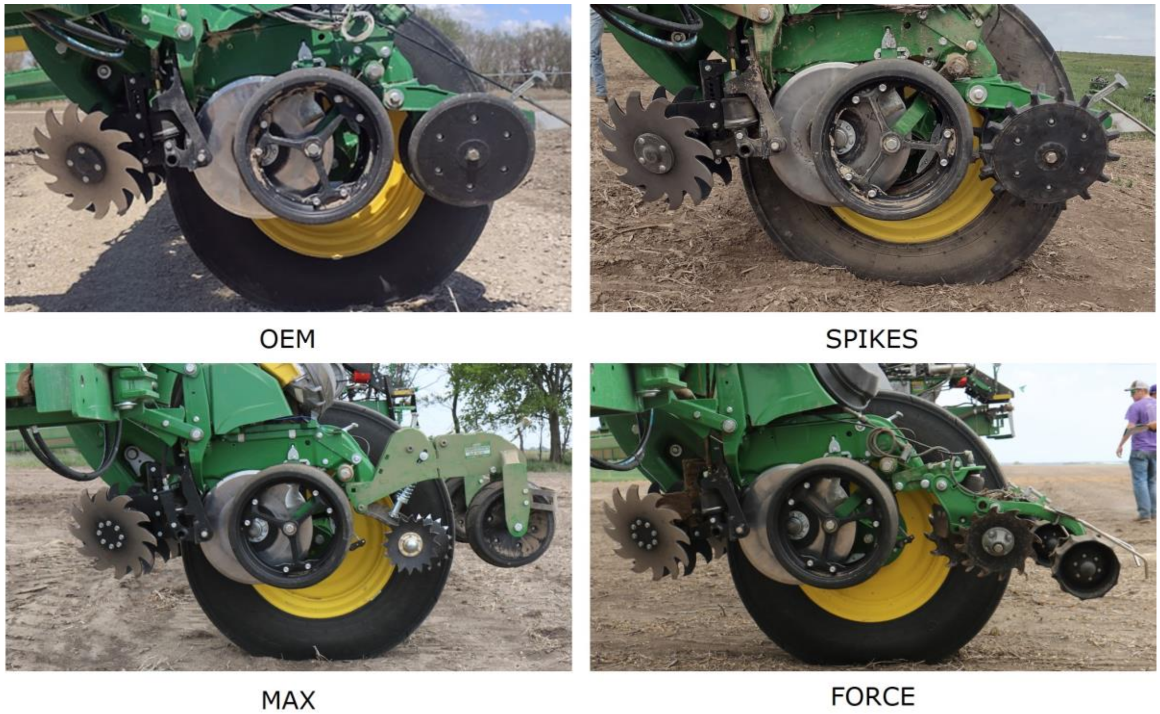

Figure 3.3. Side view of the closing wheel designs (CWD) tested in the experiment. OEM: round rubber closing wheel (Deere & Company, Moline, IL); SPIKES: Twisted Spikes wheels (Yetter Farm Equipment, Colchester, IL); MAX: Furrow Max™ closing system (Yetter Farm Equipment, Colchester, IL); FORCE: FurrowForce® closing system (Precision Planting, Tremont, IL).

The standard round rubber closing wheel (Deere & Company, Moline, IL) is referred to from here on as the original equipment manufacturer (OEM); The twisted spikes wheels (Yetter Farm Equipment, Colchester, IL) is referred to from here as SPIKES; The Furrow Max™ closing system (Yetter Farm Equipment, Colchester, IL, USA), is referred from here as MAX; and the FurrowForce® closing system (Precision Planting, Tremont, IL), is referred from here as FORCE. Working pressure regulation on the evaluated CWDs was established as follows: For the OEM and SPIKES treatments, the "T" handle was positioned in the third slot from the front of the row unit. The MAX treatment utilized two "T" handles: one for regulating the pressure of its front pinch wheels, located in the second slot from the front of the row unit, and another for controlling the pressure of the rear compacting wheel, which was also situated in the second slot from the front of the row unit. The FORCE treatment, which uses pneumatic regulation for working pressure, was set at 50 psi.

3.3.5 Post-planting data collection

3.3.5.1 Seedling labelling and emergence

After planting, 5.34 meters of experimental strips were designated within each experimental unit, specifically along the furrows established by row units 7 and 19, counting the planter's row units from left to right, as viewed from behind, as seen in Figure 3.2. Observations on plant emergence and individual plant yield metrics were conducted within these designated areas. These experimental strips were monitored twice daily, at 8:00 AM and 6:00 PM, to observe the onset and completion of plant emergence. Emergence was identified by checking for the coleoptile breaking through the soil in each strip. The initial time and date of emergence observed during the experiment in both Field A and Field B were designated as the 'beginning of emergence.' This reference point served as a critical benchmark for the subsequent analysis and interpretation of the results.

The outputs derived from these measurements encompassed the hours from the beginning of emergence as well as the Emergence Rate Index (ERI). The emergence of each seedling was analyzed using the temporal distance in hours from the 'beginning of emergence' in the respective field as a reference. This parameter will be referred to from here on as hours since the beginning of emergence (HBE). It declared its full emergence when each strip exhibited complete emergence along its length. Any visible green shoots above the ground were marked with a 10 cm long by 1 cm wide wooden stake labeled with a specific date and time code during the assessment. After full emergence, the plant identification number was recorded, corresponding to the sequence of plants from the start to the end of the strip. This was determined by noting where the planter's row unit started planting the strip and the last seed placed before the unit exited the strip based on its run direction. Following emergence, the final count recorded was 2,236 corn plants identified as the study population across all experimental units from both fields. The ERI, as introduced by Erbach (1982) and cited by Hanna et al. (2015), serves as a relative metric for evaluating the speed of corn emergence across different treatments. The ERI calculation aggregates various components, each representing the proportion of total plants that have emerged on a specific day, divided by the number of days since planting, as illustrated in Equation 3.2, where "%n" is the percentage of plants that emerged on day n; "%(n-l)" is the percentage of plants that emerged on day n-1; "n" is the number of days after planting; "first" is the number of days after planting that the first plant emerged (first counting day); "last" is the number of days after planting when emergence was considered complete (last counting date). Higher ERI values signify faster emergence rates across different fields and treatments.

$$\mathrm{ERI} = \sum_{\mathrm{n=first}}^{\mathrm{last}} \frac{[\%\mathrm{n} - \%(\mathrm{n}-1)]}{\mathrm{n}} \qquad (3.2)$$

Some limitations inherent to this methodology to measure seed emergence should be noted. The twice-daily visual observations rely on accurate identification of coleoptile emergence but may overlook seedlings that emerge between observation times or suffer early mortality shortly thereafter. Manual tagging with wooden stakes requires precise marking without disturbing the sample, whereas spatial sampling along strips may not fully capture the spatial variability of the field. Environmental factors, such as microtopography, soil moisture heterogeneity, and temperature fluctuations, can cause localized differences in emergence timing and uniformity that are not fully accounted for here. Despite these constraints, this method offers a practical and standardized approach to characterizing temporal emergence dynamics across treatments and fields, providing a robust foundation for comparative analysis.

3.3.5.2 Grain yield per plant

On September 23, 2023 (Field A) and September 4, 2024 (Field B), all corn ears within each experimental strip were systematically collected and assigned sequential numbers corresponding to their respective plant numbers within the strip. Each ear was threshed in the lab using an ALMACO Corn single-ear sheller (Nevada, IA). All the grains of each ear were weighed using an electronic scale Ruishan RSTP 3001 (Shanghai, China). The moisture content of the grains was determined by forming a sample consisting of the grains from five consecutive ears and using a portable moisture sensor Agratronix Ag-MAC PLUS (Streetsboro, OH). The moisture content was determined by deducting the wet weight of the grains from the weight of the grains linked to each ear, thereby calculating the dry weight of the grains produced. This parameter will henceforth be referred to as the individual ear grains dry weight (IEDW).

The methodology for measuring IEDW assumes uniform sheller efficiency and consistent moisture content among pooled grain samples. Variability in moisture distribution within and among ears, as well as the use of combined grain samples from multiple ears to estimate moisture, may introduce inaccuracies in dry weight calculations. Additionally, mechanical damage during shelling or handling could affect grain weight measurements. The temporal gap between harvest and measurement, and environmental factors influencing drying rates, are not explicitly controlled, potentially affecting comparability. Despite these limitations, the method provides a practical and standardized estimate of per-plant grain yield suitable for comparative analysis across treatments and fields.

3.3.6 Data analysis

EC_a and yield mapping were performed using ArcGIS Pro version 3.13 (Esri Inc., Redlands, CA). Field-collected data from post-planting sampling within experimental strips were organized and preliminarily processed using Microsoft Excel 365 (Microsoft Corporation, Redmond, WA). Subsequent statistical analyses were conducted using Python version 3.11.13 within a JupyterLab environment to enable interactive data exploration and ensure reproducibility. Data manipulation utilized the pandas library (McKinney, 2010; version 2.0.3), while inferential statistical tests—including all pairwise multiple comparisons correcting for multiple testing—were carried out with statsmodels (Seabold & Perktold, 2010; version 0.14.0) and scikit-posthocs (Terpilowski, 2019), the latter applied to perform Tukey's honest significant difference (HSD) tests. To control the family-wise error rate, a significance threshold of $\alpha = 0.05$ was strictly maintained across all hypothesis tests. For data visualization, the matplotlib (version 3.7.1) and seaborn (version 0.13.2) libraries were used to generate clear and informative graphics. Early seedling emergence probability was modeled using generalized linear models (GLM) with a binomial family and logit link function in RStudio version 2023.06.1+ (Posit PBC, Boston, MA). The model incorporated the experimental field, planter operating speed, CWD, and their interactions as predictors. Reference categories were set to 'Field A' for site, 'OEM' for CWD, and a planting speed of 12 km h^{-1}, allowing interpretable comparisons. The metrics of model performance and fit were evaluated using deviance reduction and Akaike Information Criterion (AIC). Additional diagnostics ensured the assumptions of the logistic regression model and its robustness.

3.4 Results and discussion

The results analysis identified two distinct homogenous subgroups among HBE levels: IEDW from seedlings that emerged under 48 HBE and over 48 HBE, as shown in Figure 3.4. It illustrates IEDW response to HBE, showing 15.5% and 10.66% minimum reductions in IEDW between ears from seedlings that emerged in the first 24 and 48 hours of HBE and those over 48 HBE, respectively.

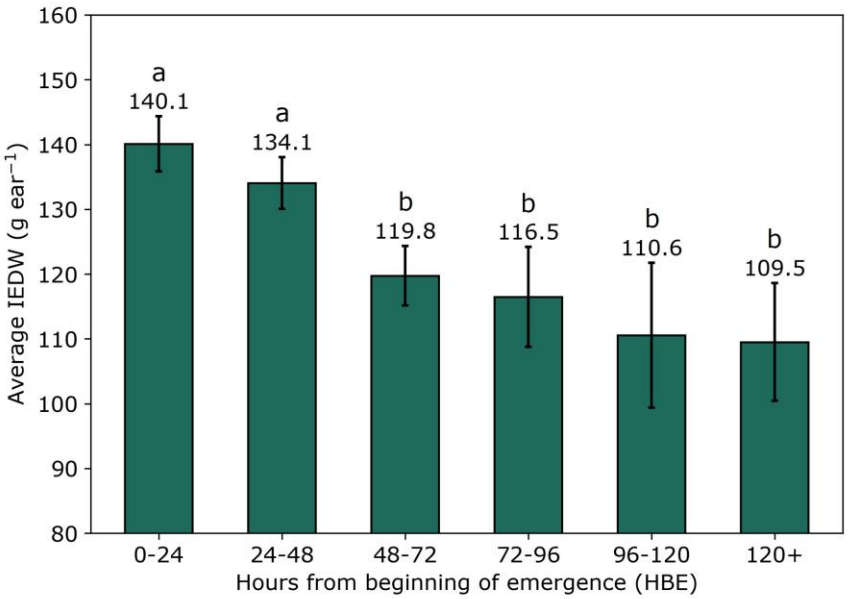

Figure 3.4. Mean grain dry weight per ear (IEDW, g ear^{-1}) response to hours since the beginning of emergence (HBE) for both fields. Results represent averages across all planter speed and closing wheels design treatments, which were not included in this analysis. Bars represent mean values with 95% confidence intervals. Lowercase letters indicate significant differences ($p<0.05$).

This significant influence of the HBE factor on the IEDW was consistent with previous findings from other authors. Dufour (2021) used a vegetative development instead of a temporal scale to measure emergence time, finding that a delay of two and four leaves resulted in a 55% and 93% reduction in ear weight, respectively, compared to the 158 g ear^{-1} produced by seedlings without any delay in emergence. Similar results were also reported by Liu et al. (2004), who observed 4% and 8% decreases in yield among seedlings that emerged from 2 and 4 leaves later than the earliest seedlings. In related findings, Novak and Ransom (2018) discovered that individual ears from plants exhibiting delayed emergence—ranging from 11 to 17 days later than earliest seedlings, with two to four leaves less developed—showed a significantly reduced yield compared to those that emerged first in the field. Ears from plants with a two-leaf delay weighed, on average, 35% less than those from the first emerged plants. Meanwhile, ears from plants approximately four leaves behind their typically emerged counterparts weighed 41% less on average. Our results indicated significant differences in the grains from the ears of plants that emerged within the first 24 and 48 HBE in both experimental fields. We observed quantitative differences of 20.3 grams in the average dry weight of grains between the seedlings that emerged in the first 24 HBE and those that emerged 48 hours later in the overall analysis of both fields, as well as a difference of 23.6 grams in the average dry weight of grains from the ears of seedlings that emerged 72 hours after the first seedlings in the experiment. Significant variation was observed in the relationship between IEDW and HBE when the data were examined separately for each experimental field. As illustrated in Figure 3.5, these field-specific differences are readily apparent.

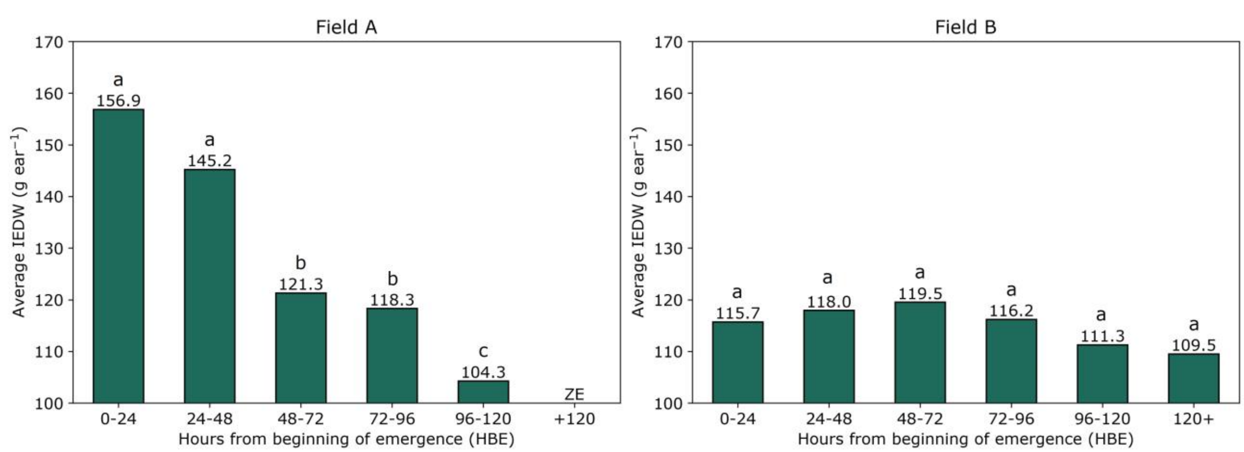

Figure 3.5. Mean grain dry weight per ear (IEDW, g ear^{-1}) by seedling emergence timing for Fields A and B. Seedlings grouped by 24-hour intervals from the beginning of emergence (HBE). Earlier emergence resulted in significantly higher grain weight in Field A but not in Field B. ZE = zero emergence (no seedlings emerged after 120 hours in Field A). Different letters indicate significant differences within each field (Tukey's HSD, α = 0.05).

A key factor underlying these patterns is the substantially later onset of emergence in Field B compared to Field A. This temporal shift is clearly explained by the ERI, which relates each seedling's emergence to days after planting (DAP). The correspondence between ERI and average IEDW is further depicted in Figure 3.6, underscoring the parallel trends between delayed emergence and reduced ear weight.

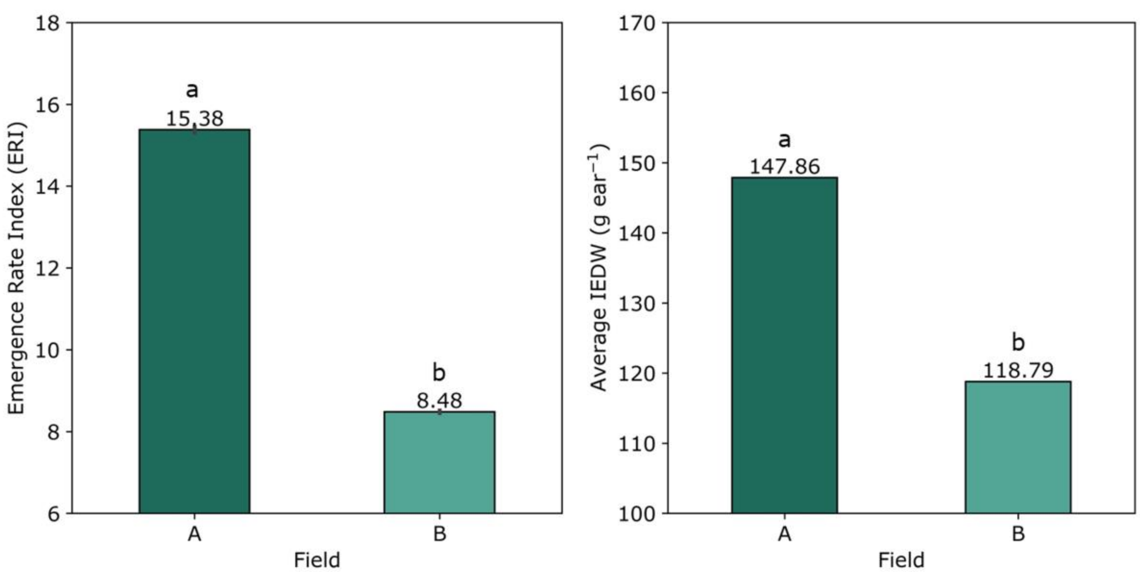

Figure 3.6. Comparison of the emergence rate index (ERI, left) and mean grain dry weight per ear (IEDW, right) between Fields A and B. ERI quantifies emergence speed, calculated as the daily incremental emergence divided by days after planting, with higher values indicating faster emergence. Field A exhibited significantly faster emergence and higher grain weight than Field B. Different letters indicate significant differences (Tukey's HSD, α = 0.05).

Despite identical planting equipment, speeds, and CWD treatments across all sites, pronounced differences persisted in emergence timing. Specifically, Field B exhibited a substantially longer interval between planting and emergence onset, as evidenced by lower ERI values. This extended period is likely associated with the lower IEDW observed in Field B, as delayed emergence substantially reduces the probability of seedlings emerging within the critical early window (defined here as within the first 48 HBE), thereby adversely affecting subsequent ear development. To further elucidate the association between field conditions and early seedling emergence, a binary logistic regression model was employed. This approach was selected because the dichotomous nature of the response variable (emerged within 48 HBE: yes/no) requires a modeling framework appropriate for binary outcomes (Hosmer et al., 2013). Unlike nonlinear logistic models commonly used to describe cumulative emergence over time (Forcella et al., 2000), binary logistic regression allows direct estimation of odds ratios and provides interpretable probabilities of early emergence across different field conditions. In this analysis, early emergence (yes/no) was the dependent variable, and field identity was a categorical predictor. The structure of the binomial logistic regression model (Equation 3.3), along with the corresponding results—including odds ratios and confidence intervals—are presented in Table 3.1. This approach enables a more quantitative assessment of how field-specific conditions influence early emergence, crop establishment, and yield components.

$$z_1 = \log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 . \mathrm{Field}_B \qquad (3.3)$$

Table 3.1. Binary logistic regression results for early seedling emergence probability (emergence within 48 hours from the beginning of emergence in the experiment) by experimental field (n = 2,236 seedlings). Field A served as reference category. Field B showed significantly lower odds of early emergence (OR = 0.09, 95% CI: 0.07-0.12, p < 0.001). β = coefficient (log-odds); OR = odds ratio; CI = confidence interval.

Variable	Coefficient (β)	Standard Error	z-value	p-value	[1] OR (95% CI)
Intercept	2.20	0.15	14.77	<0.001	9.03 (6.79-12.0)
Field B	-2.43	0.17	-14.53	<0.001	0.09 (0.07-0.12)

Note: The dependent variable was coded as 1 = early emergence and 0 = no early emergence. The reference category was Field A. [1] Odds ratios (OR) are calculated as exp(β). An OR less than 1 indicates lower odds of early emergence than the reference field, while an OR greater than 1 indicates higher odds.

The OR for Field B was calculated to be 0.09, indicating that the likelihood of early emergence in this particular field is approximately 91% lower than in Field A when all other variables are constant. The environmental context supports this strong association well: as shown in Table 3.2, climatic data from the Kansas Mesonet (Patrignani et al., 2020), indicate that Field B consistently had lower air and soil temperatures, lower relative humidity, and less solar radiation during the critical emergence period.

Table 3.2. Weather conditions during 20-day emergence periods for Field A (May 8-28, 2023) and Field B (April 19-May 9, 2024) from the Kansas Mesonet Database (Patrignani et al., 2020). Variables: air temperature (max/min), relative humidity (RH), precipitation (PRCP), wind speed (avg/max), soil temperature at 2" and 4" depths (max/min), and total solar radiation (SR). Field B had cooler temperatures and twice the precipitation of Field A.

Field	Air temp.		RH[a]	PRCP[b]	Wind speed		2” depth soil temp.		4” depth soil temp.		SR[c]
	max ºC	min ºC	avg %	mm	avg $m\ s^{-1}$	max $m\ s^{-1}$	max ºC	min ºC	max ºC	min ºC	Total $MJ\ m^{-2}$
A	25.3	12.4	67.5	70.86	2.4	18.7	25.6	17.2	23.2	17.7	21.7
B	21.1	8.2	62.8	146.04	3.3	16.1	19.2	13.3	18.1	13.9	19.5

[a] RH: relative humidity; [b] PRCP: precipitation; [c] SR: solar radiation.

Furthermore, the slower accumulation of GDD observed in Field B (Figure 3.7) indicates a thermal environment that is suboptimal for rapid emergence, directly supporting previous reports that suboptimal temperatures—both low and high—affect germination and seedling establishment in corn (Fayose & Fakorede, 2021; Schneider & Gupta, 1985; Weaich et al., 1996).

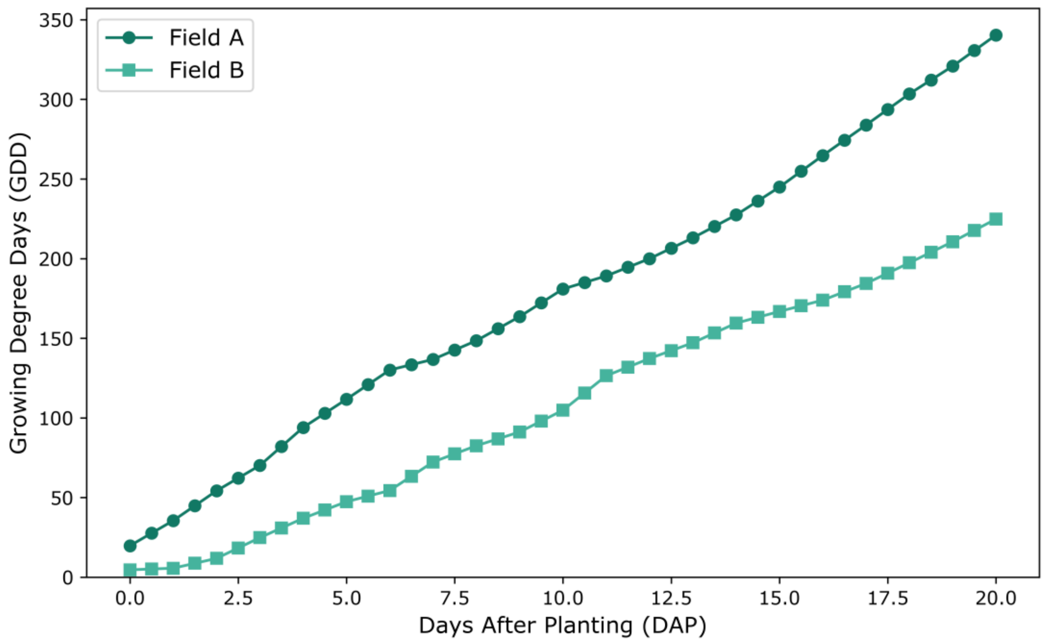

Figure 3.7. Cumulative growing degree days (GDD) during the first 20 days after planting period (DAP) for Field A (May 8-28, 2023) and Field B (April 19-May 9, 2024). GDD were calculated from daily maximum and minimum air temperatures from the Kansas Mesonet (Patrignani et al., 2020) using a base temperature of 10°C, as described by Anandhi (2016). Field A accumulated substantially more heat units (~340 GDD) than Field B (~225 GDD), contributing to faster emergence rates observed in Field A. The steeper slope for Field A indicates consistently warmer daily temperatures throughout the emergence period.

These environmental limitations delayed the onset of emergence and negatively affected crop performance, as reflected by lower IEDW at harvest in Field B. This is consistent with prior studies reporting that early corn growth subjected to low temperature stress may experience impaired emergence, slower growth, and subsequent reductions in grain yield and kernel weight (Božić et al., 2025; Domokos et al., 2024; Mohsen Khudhair & Hameed Hamza, 2024). Our findings reinforce that the environmental context has a direct and quantifiable impact on seedlings' emergence, with lasting consequences for final yield components. It is noteworthy that these differences between experimental fields were observed despite standardized planter configurations, field operations, or experimental treatments, emphasizing that even advanced planter technology cannot fully compensate for suboptimal environmental conditions at planting.

This finding confirms that the overall impact of environmental factors is highly context-specific and further modulated by interactions with plant genetics and agronomic management (Albuquerque & Carvalho, 2003; Dwyer et al., 2000). From a practical perspective, these results underline the importance of carefully considering local climatic and soil conditions for planting decisions, especially when considering early planting dates. In environments prone to low soil temperatures and slow GDD accumulation, delaying planting—even marginally—may help prevent significant yield penalties due to delayed or uneven emergence beyond the specific configuration of the planter (Norwood, 2001; Staggenborg et al., 1999).

Given this evidence that environmental conditions significantly influence early corn emergence, we also aimed to evaluate how operational treatments—specifically planter speed and CWD configuration—affect emergence outcomes under various field conditions. To accomplish this, we created a second binary logistic regression model, z_2, to evaluate the individual and combined effects of planter speed, CWD design, and field on the likelihood of early emergence throughout the experiment (Equation 3.4). Table 3.3 presents the z_2 model results and their relative importance values.

$$z_2 = \log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1.\text{Speed}_{16} + \beta_2.\text{Spikes} + \beta_3.\text{Force} + \beta_4.\text{Max} + \beta_5.\text{Field}_b + \beta_6.(\text{Speed}_{16}.\text{Spikes})$$
$$+\beta_7.(\text{Speed}_{16}.\text{Force}) + \beta_8(\text{Speed}_{16}.\text{Max}) \qquad (3.4)$$

Table 3.3. Binary logistic regression for early emergence probability (within the first 48 hours from emergence start in the experiment) by speed, closing wheel design (CWD: OEM, SPIKES, FORCE, MAX), and field (n = 2,236 seedlings).

Variable	Coefficient (β)	Standard Error	z-value	p-value	[1] OR (95% CI)
Intercept	3.01	0.23	13.05	<0.001	20.30 (12.92-31.90)
16 km h^{-1}	-0.38	0.23	-1.70	0.096	0.68 (0.43-1.07)
SPIKES	0.13	0.32	0.40	0.695	1.14 (0.60-2.14)
FORCE	-1.43	0.28	-5.20	<0.001	0.24 (0.14-0.21)
MAX	-0.54	0.25	-2.13	<0.05	0.58 (0.36-0.96)
Field B	-2.68	0.18	-14.84	<0.001	0.07 (0.05-0.10)
16 km h^{-1} * SPIKES	-1.25	0.43	-2.93	<0.01	0.29 (0.12-0.68)

16 km h^{-1} * FORCE	0.57	0.39	1.48	0.138	1.77 (0.83-3.79)
16 km h^{-1} * MAX	0.44	0.36	1.22	0.220	1.56 (0.77-3.16)

Note: The dependent variable, early emergence, was coded as 1 = early emergence, 0 = no early emergence. Reference categories are: Speed = 12 km h^{-1}, CWD = OEM, Field A. Odds ratios (OR) are calculated as exp(β). An OR less than 1 indicates lower odds of early emergence than the reference category, while an OR greater than 1 indicates higher odds.

Equation 3.5 determined the modeled probability (p) of early emergence from z_2, and the findings are presented in Figure 3.8.

$$p = \frac{1}{1-e^{-z_2}} \qquad (3.5)$$

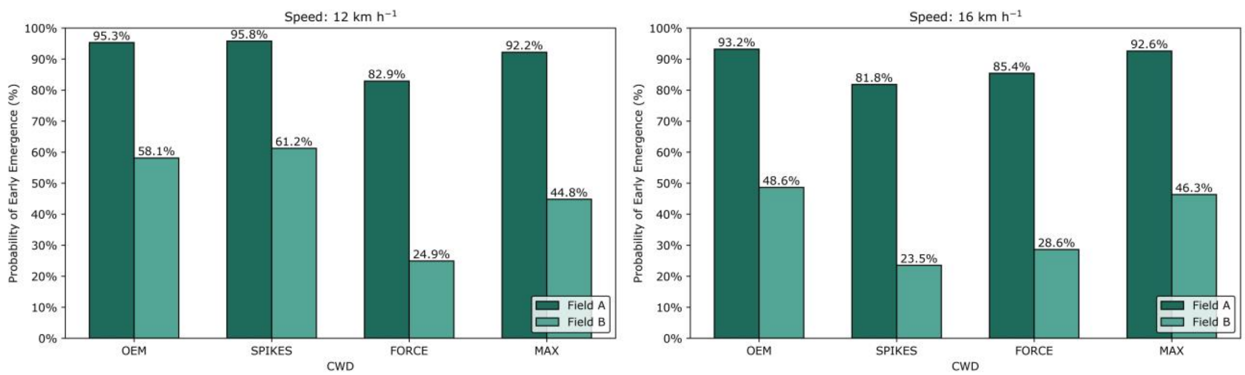

Figure 3.8. Modeled probability of early corn seedling emergence (within the first 48 hours from emergence start in the experiment) at 12 km h⁻¹ (left) and 16 km h⁻¹ (right), for each CWD and field. Probabilities from the binomial logistic regression (model z_2); bars show each CWD (OEM, SPIKES, FORCE, MAX). All other variables are constant.

These values, derived from the modeled probability based on z_2, are corroborated with the actual emergence percentages obtained in the first 48 HBE in the experimental strips of both fields, as shown in Figure 3.9.

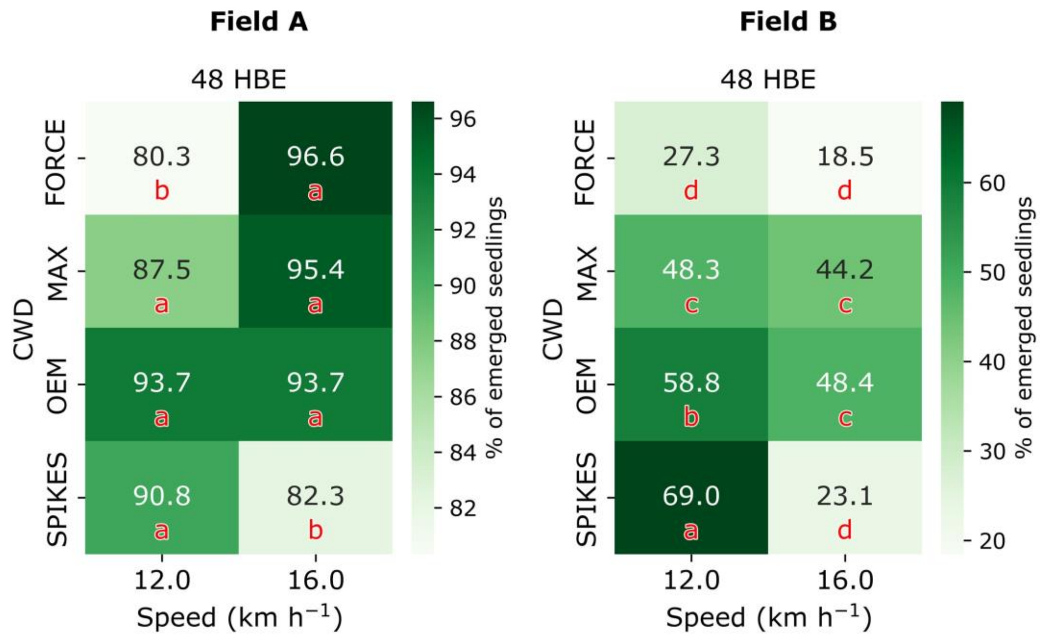

Figure 3.9. Early emergence percentage (within the first 48 hours from emergence start in the experiment) by closing wheel design (CWD) and speed for Fields A and B. Darker shading indicates higher early emergence. Color scales differ between fields (A: 80-97%, B: 18-70%). Field A showed high early emergence across treatments, while Field B had lower early emergence, especially with SPIKES at 16 km h^{-1}. Different letters within each field indicate significant differences (Tukey's HSD, α = 0.05).

Our results regarding early corn seedling emergence underscore the significant impact of planter operating speed on establishment success. Consistent with prior studies documenting the adverse effects of increased planting speed on emergence uniformity and timing (Celik et al., 2007; Liu et al., 2004a; Novak & Ransom, 2018; Staggenborg et al., 2004), the predicted probabilities from our logistic model indicate a general decline in early emergence likelihood as planter speed increases from 12 to 16 km h^{-1} across all CWD. At the lower speed of 12 km h^{-1}, early emergence probabilities were uniformly high, exceeding 82% for all CWD treatments and surpassing 95% in some instances. However, increasing operating speed to 16 km h^{-1} significantly reduced these probabilities, exhibiting the steepest declines with the SPIKES design (from 95.8% to 81.8%) and moderate reductions for FORCE and MAX designs. This decline in emergence probability at higher speeds aligns closely with previous findings that faster planting rates can compromise seed placement accuracy, reduce seed-to-soil contact quality, and impair furrow closing effectiveness, collectively contributing to increased emergence variability and delays (Liu et al., 2004a; Marques Filho & Ventura, 2021). Such observations also reflect agronomic recommendations that advocate for conservative planting speeds—typically below 7 km h^{-1}—to ensure uniform seedling emergence and maximize yield potential (Garcia et al., 2006; Kuş, 2021). Our results suggest that surpassing these speed thresholds, even with advanced planter components, may jeopardize early stand establishment. Moreover, the significant interaction observed between high planting speed and CWD highlights the necessity of careful calibration of planter settings to operational velocity to mitigate negative emergence effects.

Complementing the influence of speed, the logistic regression analysis revealed that the choice of furrow closing device substantially affects early emergence probability. Specifically, the FORCE and MAX designs were associated with pronounced decreases in the odds of early emergence relative to the OEM baseline, reducing the likelihood by approximately 76% and 42%, respectively. Although the SPIKES design did not exhibit a significant main effect compared to OEM, its interaction with increased planting speed further and significantly exacerbated reductions in early emergence probability. These findings accord with established agronomic principles emphasizing that adequate and uniform furrow closure is essential to promote seed-to-soil contact and moisture conservation—critical conditions for rapid and uniform seedling emergence. This is particularly relevant in challenging settings such as no-till systems, where the presence of surface residue and heterogeneous soil structure can hinder germination and establishment (Iqbal et al., 1998; Pavlov et al., 2022; Way et al., 2018). Furthermore, our results resonate with recent innovations in furrow closing technologies, which have sought to improve seedbed microenvironments through modifications to closing wheel design, row packing mechanisms, and soil-covering attachments (Drewry et al., 2020; Geng et al., 2022; Radnaev et al., 2022). Nevertheless, the observations that FORCE and MAX reduced early emergence odds despite their expected soil coverage benefits underscore the complex nature of emergence dynamics. These results suggest that enhanced furrow closure does not universally translate into improved early stand establishment and that field-specific conditions—such as soil texture, moisture availability, and residue cover—play critical roles in modulating the agronomic effectiveness of different closing designs (Hanna et al., 2015; Lu et al., 2024; Shepelev et al., 2024). Accordingly, the selection of furrow closing devices should be made with site-specific factors and management practices in mind to optimize uniform emergence and ultimately maximize yield potential.

Our findings highlight that planter operating speed and furrow closing device design intricately influence early corn seedling emergence. Moderation of planting speed and careful matching of closing device technology to field conditions emerge as key management strategies to promote consistent stand establishment and support productive crop outcomes.

3.4.1 Discussion of uncertainty and methodological limitations

The measurements of seedling emergence and IEDW provided valuable insights into planter performance and crop establishment. However, several limitations and sources of uncertainty must be acknowledged. Seedling emergence assessments assumed accurate identification of live seedlings at declared emergence stages, but delayed germination or early mortality could affect IEDW estimates of the adjacent plants. Variability in field microclimates and soil conditions across experimental sites influenced emergence timing and uniformity, complicating causal attributions to planter treatments. Grain yield per plant, measured as individual ear dry weight, relied on uniform shelling efficiency and representative moisture sampling; variations in moisture content within ears and sampling pooling may introduce bias. Moreover, operational factors such as planting speed and CWD exerted significant, interacting effects on emergence probability, with higher speeds generally reducing early emergence uniformity. While some closing wheel designs improved seedbed microenvironments, their agronomic efficacy was context-dependent, influenced by soil texture, moisture, and variability in residue cover. These factors collectively contribute to measurement variability and introduce uncertainty in separating treatment effects from environmental influences.

3.5 Conclusions

This study highlights the multifaceted nature of factors influencing early corn seedling emergence and subsequent stand establishment. Both planter operating speed and CWD significantly affect the probability of early emergence, with higher speeds (16 km h^{-1}) generally reducing emergence likelihood across all CWDs. Notably, the SPIKES design, although not significantly different from OEM at lower speeds, markedly decreased early emergence probability when combined with increased planting speed. Similarly, the FORCE and MAX CWDs consistently reduced early emergence odds compared to OEM, reflecting the critical role of proper furrow closure in optimizing seed-to-soil contact and moisture retention for uniform seedling development.

Importantly, these operational effects occur within the broader context of environmental variability, which the study identifies as a primary determinant of emergence dynamics and yield components. Site-specific conditions—particularly soil temperature and moisture in the days immediately following planting—exert a strong influence on emergence timing and final individual ear dry weight (IEDW). Our findings demonstrate that, even with standardized planter configurations and CWD treatments, less favorable environments such as those observed in Field B can delay emergence and reduce yield potential, underscoring the limitations of agronomic and technological adjustments in overcoming adverse climatic factors during establishment.

Together, these results emphasize the need for integrated management strategies that consider both environmental assessments and careful calibration of planter speed and closing device selection. Moderating planting speed and matching CWD design to site-specific soil and residue conditions are essential to promote rapid and uniform emergence, thereby supporting consistent stand development and maximizing yield potential. The study advocates for continued research and development focused on optimizing the interaction between machine settings and environmental conditions, ensuring adaptability across diverse agroecosystems.

Chapter 4 - Effects of planter speed and closing wheel design on corn seed placement and population uniformity across variable field environments

4.1 Abstract

This study evaluated the effects of planter speed and closing wheel design (CWD) on seed placement precision, plant spacing uniformity, and live plant population in corn across two contrasting field conditions in North-central Kansas, USA. Treatments included four CWD types (‘OEM’, ‘SPIKES’, ‘FORCE’, and ‘MAX’) operated at two planter speeds (12 and 16 km h^{-1}). Key performance indicators measured were quality of feed index, singulation error rates, seed depth distribution, plant spacing variability, and percentage of target plant population achieved (PTPA). Results demonstrated that both CWD and planter speed significantly influenced seed placement accuracy and uniformity, with ‘MAX’ and ‘SPIKES’ systems generally outperforming others by maintaining higher quality of feed indices and lower miss and multiple seed indices, especially at elevated speeds in Field A. In contrast, the ‘FORCE’ system exhibited reduced performance at higher speeds. Field B results highlighted the importance of site-specific interactions, where ‘OEM’ at 12 km h^{-1} and ‘MAX’ at 16 km h^{-1} provided optimal outcomes. Furthermore, precise seed placement within an optimal depth range (~38–63.5 mm) correlated with superior individual plant yield values. Higher planting speeds negatively impacted the PTPA for certain CWDs, emphasizing the need for appropriate calibration. Collectively, findings underscore that selecting and calibrating planter components by considering operational speed and field conditions are critical for optimizing live plant population establishment and yield

potential in corn crops. This research provides actionable insights for improving precision in seed placement under variable agronomic contexts.

4.2 Introduction

Precision in seed placement is fundamental to achieving optimal yield in modern row crop agriculture, particularly for corn. A substantial body of research has explored optimal planting depths for corn within the American Midwest, with consensus generally converging on a range of 50.8–76.2 mm to ensure robust establishment under most environmental conditions (Sassenrath et al., 2020; Stewart et al., 2021). Deeper planting, approaching to 76.2 mm, often enhances emergence uniformity and yield, especially in fine-textured soils and during periods of elevated temperature, whereas deviations from this recommended range—either too shallow or too deep—can reduce yields (Sassenrath et al., 2020). Planting depth uniformity has also been shown to be more critical for subsequent yield outcomes than initial seed size distribution (Kimmelshue et al., 2022a), although some compensatory mechanisms within the crop may mitigate final yield penalties where depth uniformity is compromised (Stewart et al., 2021). Planting depth, however, is subject to a complex interplay of mechanical and environmental factors. Soil temperature and matric potential directly affect seedling emergence rates, and deeper placement increases the thermal time required for emergence (Gupta et al., 1988). Among mechanical variables, planter speed is particularly influential. A consistent theme across agronomic research is that higher planter speeds generally compromise both the consistency of seed planting depth and overall placement accuracy (Kuş, 2021; Nadin et al., 2019; Staggenborg et al., 2004). Lower planter speeds (typically 4–6 km h^{-1}) enable greater uniformity in seed depth and spacing (Ahmed et al., 2023; Badua et al., 2018), although the optimal speed can vary with planter type and prevailing field conditions. Additional factors such as downforce settings, seed metering units, and seed hopper fill level further modulate planting depth consistency (Ahmed et al., 2023; Virk et al., 2020). The impact of planter speed is also strongly evident in the resulting plant-to-plant spacing within the row. Numerous studies have demonstrated that increased operating speeds amplify variability in seeded spacing, as reflected by higher coefficients of variation and reduced placement indices (Liu et al., 2017; Moody et al., 2003; Nielsen, 1995; Staggenborg et al., 2004). Uniformity in plant spacing is essential not only for optimizing stand establishment, but also for achieving potential yield benefits, particularly in corn (Liu et al., 2004a; Nielsen, 1995). Double seeds (multiple index), missed seeds (miss index), and other performance metrics such as the quality of feed index and the precision index are all adversely affected by faster planter speeds (Ahmed et al., 2023; Kuş, 2021; Liu et al., 2017). Of particular note, the use of seed firming devices and improved mechatronic seed meters may mitigate some negative effects of speed, helping to preserve placement accuracy in varying conditions (Li et al., 2015; Staggenborg et al., 2004). Planter type further influences these outcomes, with vacuum meter designs typically outperforming alternative mechanisms (Liu et al., 2017; Liu et al., 2004a). The role of the closing wheels design in optimizing seed placement has garnered increasing research attention, particularly as no-till and conservation tillage practices become widespread. Novel closing wheel geometries, such as star-tooth spherical discs, have been proposed to improve seed-soil contact and coverage uniformity (Lu et al., 2024). Empirical findings suggest that aftermarket closing wheels can enhance seedling emergence by improving soil cover relative to conventional rubber wheels, especially in high-residue no-till systems (Drewry et al., 2020, 2021). However, effects can be crop- and context-specific, as not all closing wheel types produce measurable differences in emergence or placement in every crop or tillage regime (Way et al., 2018). Beyond emergence, the position and shape of depth control wheels and closing components can substantially affect seed placement depth and uniformity (Morrison & Gerik, 1985), mediated by interactions with forward speed, disc tilt, and penetration depth (Lu et al., 2024). The soil load characteristics on the row unit elements in contact with it and the type of crop residue also play a key role in the final seed placement (Doan et al., 2005; H. M. Hanna et al., 2010). The interplay of planter speed and closing wheel design further impacts stand establishment and final plant population—a critical determinant of yield in corn and other row crops. Increased planter speeds, in general, elevate the incidence of plant spacing variability, missed seeds, and multiples, often leading to a decline in the percentage of plants spaced within acceptable limits (Garcia et al., 2006; Liu et al., 2004a; Nadin et al., 2019; Staggenborg et al., 2004). While yield reductions of 0.08–0.20 t ha^{-1} per km h^{-1}increase in speed have been documented in corn (Nielsen, 1995), the effect in soybean and other crops may be less pronounced (Dias et al., 2009). The live plant population significantly influences corn grain yield (Haarhoff and Swanepoel 2018). The performance of the planter—governed by type, maintenance, and setup—remains crucial for achieving a uniform final live plant population and for maximizing crop profitability (Fawcett et al., 2017; Liu et al., 2004a). Uniform spacing and establishment are promoted by slower planting speeds (typically below 7 km h^{-1}), careful adjustment of planter mechanisms, and selection of closing wheels suited to field conditions (Ferreira et al., 2019). In summary, planting depth, in-row spacing accuracy, and final live plant population are interconnected outcomes resulting from planter operational speed, closing wheel design, and related agronomic management practices. Understanding these relationships is crucial for developing recommendations that improve seed placement quality, stand uniformity, and ultimately increase yield in corn and other row crops. Despite significant advances in planter technology and a growing body of research addressing isolated effects of planting depth, speed, and closing wheel design, comprehensive studies that measure their combined impact on key indicators of seed placement and stand establishment are still limited. Most existing research has examined these factors individually or in specific contexts, leaving unanswered important questions about their interactions, optimal setups, and effects on modern planting practices. This study aims to systematically evaluate the impact of planter operating speed and closing wheel design on critical parameters of planting quality, including seed placement depth, in-row plant spacing, and live plant population achieved, in corn sown under representative field conditions of Northcentral Kansas in the American Midwest. Specifically, the research objectives are to: i) Quantify the effects of different planter speeds and closing wheel designs on the uniformity of seed placement depth; ii) Analyze how these factors influence the accuracy and variability of plant-to-plant spacing; and iii) Integrate findings related to depth, spacing, and establishment metrics to assess the implications for final live plant population.

Through extensive field experimentation and data analysis, this paper aims to provide empirical evidence to inform agronomic best practices and recommendations for speed settings and closing wheel designs in corn planters. It ultimately seeks to improve planting quality to maximize plant development potential in corn production systems.

4.3 Materials and methods

4.3.1 Experiment design

The experiment was conducted using a split-plot design within a randomized complete block arrangement, consisting of three replications (blocks). The main plot factor was planter speed, with two levels: 12 km h^{-1} and 16 km h^{-1}. The subplot factor comprised four different closing wheel designs (CWD) treatments, each assigned within the main plots.

4.3.2 Site description

Field trials were conducted in 2023 and 2024 in Exeter Township, Clay County, north-central Kansas, USA. Two sites were evaluated: Field A (39.239884 °N, 97.234797 °W; 54.98 ha total, 13.43 ha experimental area) with soils classified as 48.6% Crete silt loam (3775), 42.6% Crete silty clay loam (3802), and 8.8% Muir silt loam (3775); and Field B (39.305457 °N, 97.176462 °W; 27.26 ha total, 12.53 ha experimental area), comprising 64.3% Crete silty clay, 1–3% slopes (3828), and 35.7% Crete silty clay loam, 3–7% slopes (3802) according to USDA et al. (2025). Field A was planted on May 8, 2023, targeting a plant population density of 54,834 plants ha^{-1}, while Field B was planted on April 19, 2024, with a target population density of 54,340 plants ha^{-1}. Both sites were managed as dryland, no-till systems in a corn–soybean rotation initiated in spring 2020. Soil moisture content was measured at each experimental strip inside each field using a HydroSense II Handheld Soil Moisture Sensor (Campbell Scientific, Logan, UT), which provides real-time readings of volumetric water content in situ and data storage for subsequent analysis. Two measurements were taken for each strip, one at each end, to characterize moisture variability along the treatment area. The measurements were performed according to manufacturer specifications, ensuring consistent probe insertion depth and contact with the surrounding soil matrix. The soil moisture measurements, as depicted in Figure 4.1, reveal distinct differences between the two experimental fields at planting. Field A exhibited a higher mean volumetric soil moisture content (42.76%), whereas Field B showed a lower average value (38.39%). The boxplot also indicates broader variability in Field B compared to Field A, as evidenced by a greater interquartile range and whisker extension.

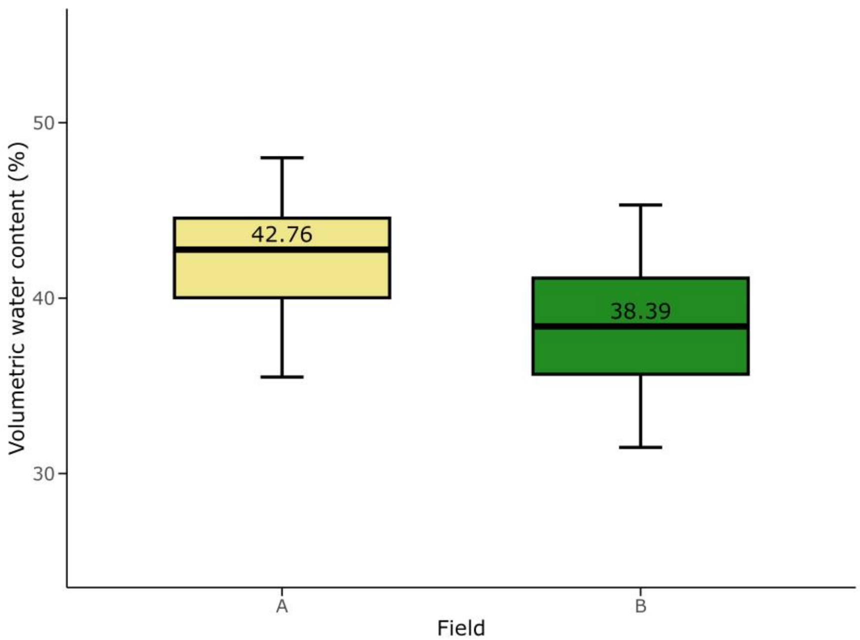

Figure 4.1. Volumetric water content response was observed in both experimental fields. Boxes represent the interquartile range (25th to 75th percentiles), horizontal lines within boxes indicate medians, and whiskers extend to 1.5× the interquartile range. Outliers were excluded from the plot.

4.3.3 Row-crop planter

Field operations were carried out with a John Deere 1775NT 24row30 planter (Deere & Company, Moline, IL), configured with 24 individual row units spaced 762 mm apart and powered by a John Deere 8R 410 tractor (Figure 4.2). The planter was equipped with a SeedStar™ 4HP monitoring system for operational control. Each row unit incorporated ExactEmerge™ technology with a BrushBelt™ delivery mechanism, designed to transfer seed from the metering device directly into the furrow, thereby reducing seed bounce and enhancing placement precision. Seed metering was based on electrically driven units, while hydraulic downforce was applied individually to each row unit to ensure consistent soil engagement across varying field conditions. The downforce margin selected for the experiments was 800 N. To improve seed flow, Talc 80/20 (a graphite–talc lubricant) was mixed with seed at a rate of 38 g per 80,000 seeds during all planting operations. Row cleaners were adjusted to a light-to-medium setting appropriate for the prevailing residue and soil conditions.

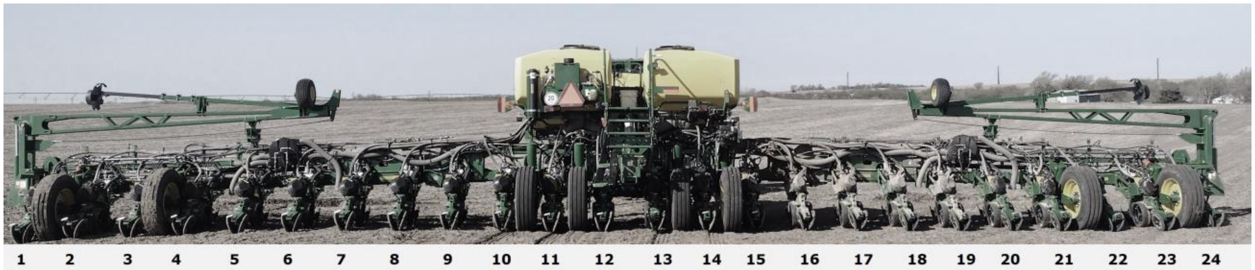

Figure 4.2. John Deere 1775 NT planter with sequential row unit identification (1-24) for individual data tracking.

Seed depth calibration was performed before planting using a calibration tool (Set-N-Seed, Oakdale, IL), with the target depth set at 50.8 mm for all treatments. The target seed depth range (TSDR), was defined as ±6.35 mm from the target to reflect practical field conditions, resulting in a threshold band between 44.5 mm and 57.1 mm. This range was selected based on agronomic considerations, recognizing that seeds placed within these limits could be regarded as having been sown at the correct depth for optimal establishment.

4.3.4 Closing wheel designs

Four distinct CWD were tested in this study, comprising one original equipment manufacturer design (‘OEM’), and three aftermarket alternatives for furrow closure and coverage. These devices were assigned to 12 consecutive rows on either the right or left half of the planter, with the assignment randomized for each experimental run. The evaluated systems included: (1) the standard round rubber wheel (Deere & Company, Moline, IL), identified as ‘OEM’; (2) twisted spikes wheels (Yetter Farm Equipment, Colchester, IL), referred to hereafter as ‘SPIKES’; (3) the Furrow Max™ system (Yetter Farm Equipment, Colchester, IL), denoted as ‘MAX’; and (4) the FurrowForce® system (Precision Planting, Tremont, IL), referred to as

‘FORCE’. Each CWD was calibrated for operating pressure based on manufacturer guidelines. The “T” handle was set to the third notch from the front of the row unit for ‘OEM’ and ‘SPIKES’ wheels. The ‘MAX’ closing system utilized two independent “T” handles, both positioned in the second slot from the front—one controlling the front pinch wheels and one for the rear compacting wheel. In the ‘FORCE system’, pneumatic pressure was regulated at 50 psi throughout all treatments (Figure 4.3).

Figure 4.3. Rear view of the closing wheel designs (CWD) tested in the experiment. OEM: round rubber closing wheel (Deere & Company, Moline, IL); SPIKES: Twisted Spikes wheels (Yetter Farm Equipment, Colchester, IL); MAX: Furrow Max™ closing system (Yetter Farm Equipment, Colchester, IL); FORCE: FurrowForce® closing system (Precision Planting, Tremont, IL.

4.3.5 Data collection and measurements

4.3.5.1 In-row plant spacing measurement

In the V1 seedling phase, vegetative state identified according to according to Ciampitti et al. (2016), plant spacing was assessed using a standard measuring tape (Stanley Black & Decker, New Britain, CT) that measured 7.6 meters in length. The tape was positioned along the experimental strip, and measurements for the total spacing were recorded. The theoretical plant spacing (TS) for each experimental field was determined based on the seeding rate and the spacing between planter row units according to Badua et al. (2021). The TS values were 238.4 mm for Field A and 242.3 mm for Field B. The current study employed measurements of plant spacing uniformity based on the indices described in ISO 7256/1-1984(E) by Kachman & Smith (1995), as referenced by Badua et al. (2021). These indices include the multiple index, miss index, quality of feed index, precision index (referred to here as the variability index), and the coefficient of variation. The multiple index indicates the number of spacings on each experimental strip that are less than or equal to 0.5 times the TS. The miss index quantifies the number of spacings on each experimental unit that exceed 1.5 times the TS. The quality of feed index, also known as the single plant index, assesses how closely the measured spacing aligns with TS by calculating the proportion of spacings on each experimental strip that fall within the range of 0.5 to 1.5 times the TS. The variability index measures how consistently plants are spaced, considering skips, doubles, and singles, with lower values indicating less variability in spacing. Lastly, the coefficient of variation (CV) is a key metric for assessing plant spacing uniformity in crop rows, with lower CV values indicating better uniformity (Bisognin et al., 2019; Stewart et al., 2021).

This approach assumes that the measured plant spacings accurately reflect the actual spatial distribution along the row, with minimal alteration from post-emergence plant movement or mortality. The method presupposes uniform planter operation, delivering consistent seed placement per TS, and assumes manual measurement accuracy despite potential influences from row curvature, field irregularity, and operator bias. Sampling focused on strips may not capture whole-field variability, and spacing indices do not account for temporal changes resulting from delayed emergence or plant mortality. Overall, while providing standardized comparative metrics, measurement and sampling assumptions limit the complete characterization of spatial and temporal spacing variability.

4.3.5.2 Live plant population

Once 100% emergence was confirmed in each experimental strip, the number of seedlings was counted to calculate the percentage of the target population achieved (PTPA) for each treatment combination and experimental site. This method assumes complete and accurate identification of living seedlings at full emergence, excluding late emerging or dormant seeds. It treats emergence as a static event, without accounting for post-emergence plant mortality or damage. Moreover, it assumes that initial seeding rates are uniform and that seed placement variability is minimal within the strip.

4.3.5.3 Seed depth measurement

The depth of seeds at the V1 seedling stage was manually measured by calculating the vertical distance from the center bottom of each seed to the soil surface within each experimental strip. A wooden marker simulating the gauge wheel pressure (2.8 mm thick, 300 mm long, 28.2 mm wide) was placed perpendicular to the planting direction on the surface residue to establish a consistent reference point. Depth was then measured using a digital caliper (SYLVAC IP67, Malleray, Switzerland), aligned with the top of the marker. This approach assumes the wooden marker accurately replicates row unit soil contact pressure and surface conditions, and that the soil surface around seedlings is level enough to allow consistent depth measurements. Variability in soil clod size and residue cover, as well as human measurement precision, may introduce measurement error. Additionally, depth measurements were confined to a specific early growth stage (V1), which might not capture later seed displacement due to soil settling or mechanical disturbance.

4.3.5.4 Grain yield per plant

On September 23, 2023 (Field A) and September 4, 2024 (Field B), ears of corn were systematically harvested from every plant within each experimental strip. Each ear was assigned a unique identifier corresponding to its plant position within the strip. In the laboratory, ears were shelled individually using an ALMACO Corn single-ear sheller (Nevada, IA). The total grain yield per ear was recorded by weighing all grains on a Ruishan RSTP 3001 electronic scale (Shanghai, China). To determine grain moisture content, samples were formed by combining kernels from five consecutive ears and analyzed with an Agratronix Ag-MAC PLUS portable moisture meter (Streetsboro, OH). Dry grain weight for each ear was then calculated by adjusting the measured wet weight for the ear's moisture content. This metric is referred to throughout the study as individual ear dry weight (IEDW). This approach assumes uniform shelling efficiency and accurate moisture sampling representing the five-ear pool. Limitations include potential variation in moisture within ears or along the experimental strip, sampling bias due to ear pooling, and the implicit assumption that ear dry weight directly reflects individual plant yield without accounting for potential post-harvest grain loss or variation in grain density.

4.3.6 Statistical analysis

Field-collected post-planting sampling data from experimental strips were organized and initially processed using Microsoft Excel 365 (Microsoft Corporation, Redmond, WA). A factorial analysis of variance (ANOVA) was conducted to assess the effects of planter speed, CWD, and their interaction on the measured response variables. To identify statistically significant differences among treatment combinations, Tukey’s post-hoc test for multiple comparisons with type I error correction was applied. Both the base R Studio (version 2023.06.1+; Posit PBC, Boston, MA) function TukeyHSD and the ‘agricolae’ package were utilized to perform these analyses and to generate grouping letters for visual interpretation of treatment differences.

4.3.6.1 Binomial logistic regression for target seed depth range assessment

A binomial logistic regression model was fitted to evaluate the probability of placing seeds within the TSDR. The response variable, the TSDR, was created as a binary indicator taking the value 1 when the observed seed depth was within the specified TSDR, and 0 otherwise. The model included the main effects of planter speed and CWD, as well as their interaction, to assess whether the impact of planter speed on seed depth varied across different closing designs. Both predictor variables were treated as categorical factors, with the reference levels set to 12 km h^{-1} for planter speed and ‘OEM’ for CWD. The fitted logistic regression model is shown in equation 4.1.

$$\eta = \log\left(\frac{p}{1\text{-}p}\right) = \beta_0 + \beta_1.\text{Speed}_{16} + \beta_2.\text{Spikes} + \beta_3.\text{Force} + \beta_4.\text{Max} + \beta_5.\left(\text{Speed}_{16}.\text{Spikes}\right) + \beta_6.\left(\text{Speed}_{16}.\text{Force}\right) + \beta_7.\left(\text{Speed}_{16}.\text{Max}\right) \quad (4.1)$$

Where the logit function represents the log-odds of placing seeds within TSDR, ‘Speed_{16}’ is a dummy variable indicating planter speed of 16 km h^{-1} (compared to the reference treatment of 12 km h^{-1}). ‘SPIKES’, ‘FORCE’, and ‘MAX’ represent dummy variables for the CWD compared to the reference ‘OEM’. The model was estimated using generalized linear models (GLM) with a binomial family and logit link function in R Studio. Statistical significance of coefficients was assessed via Wald tests. The coefficients derived from the binomial logistic regression model, represented in log-odds, were transformed into probabilities using the inverse logit (sigmoid) function to estimate the likelihood of placing seeds within TSDR. Specifically, for each treatment combination, the linear predictor—the sum of the intercept, main effects, and pertinent interaction terms—was exponentiated and appropriately scaled, as illustrated in

Equation 4.2, where "p" is the probability and "η" is the linear predictor value, this allowed computation of the modeled probability of placing seeds within TSDR for each combination of planter speed and CWD treatments.

$$p = \frac{e^{\eta}}{1+e^{\eta}} \qquad (4.2)$$

4.4 Results and discussion

4.4.1 In-row plant spacing accuracy

Within-row plant spacing accuracy is a fundamental determinant of crop performance in corn, as irregularities in seed horizontal placement can lead to suboptimal plant development and yield penalties. In this section, we present the results of key planting accuracy metrics—including miss index, double index, quality of feed index, variability index, and the coefficient of variation—for each combination of planter speed and CWD evaluated at both experimental sites. The mean values for the first three indicators, summarized in Tables 4.1 and 4.2 for Field A and Field B, provide an initial assessment of how machine configuration and operating speed affected singulation performance and seed delivery quality under contrasting site conditions.

Table 4.1. In-row plant spacing metrics by closing wheel design (CWD) and planter speed in Field A, measured manually and calculated per ISO 7256/1-1984 standard with target spacing of 238.4 mm. Metrics: mean spacing, coefficient of variation (CV), Multiple index (< 119.2 mm), Miss index (> 357.6 mm), Quality of feed (119.2-357.6 mm), and Variability index. Different letters within columns indicate significant differences (Tukey's HSD, α = 0.05). Higher quality of feed index and lower miss/multiple indices indicate superior planting uniformity.

CWD	Planter speed (km h^{-1})	Multiple index (%)	Miss index (%)	Quality of feed index (%)
OEM	12	1.59 b	9.52 a	88.90 b
	16	1.59 b	7.93 b	90.50 b
SPIKES	12	1.54 b	6.15 c	92.30 a
	16	0.00 c	8.06 b	91.93 a
FORCE	12	0.00 c	9.83 a	90.16 b
	16	3.39 a	10.17 a	86.44 c
MAX	12	3.13 a	4.69 d	92.18 a
	16	3.08 a	6.15 c	90.80 b

Results in Table 4.1 revealed differences attributable to planter speed and CWD treatment. The ‘SPIKES’ and ‘MAX’ treatments consistently achieved the highest quality of feed index (>91.9%) across speeds, indicating a superior overall singulation performance. In contrast, the ‘FORCE’ system at 16 km h^{-1} recorded the lowest quality of feed index (86.44%), principally due to a marked increase in multiple index (3.39%) and persistent high miss index (10.17%). Miss index values varied significantly among treatments and speeds, with ‘MAX’ at 12 km h^{-1} producing the lowest value (4.69%), and ‘FORCE’ and ‘OEM’ at either speed displaying elevated miss rates (>9.5%). Notably, ‘SPIKES’ at 12 km h^{-1} achieved the lowest miss index (6.15%) among all conventional designs. In comparison, at 16 km h^{-1}, its multiple index was reduced to zero, suggesting optimal feed quality in this configuration. Multiple index percentages were generally low across treatments, except for the ‘MAX’ and ‘FORCE’ devices at both speeds, which exhibited slightly higher values, indicating a greater propensity for double seed drops under some conditions. Overall, these findings demonstrate that both planter speed and CWD treatment exert significant influence over the precision of seed horizontal placement, with the ‘MAX’ and ‘SPIKES’ systems providing consistently high planting accuracy within Field A, while ‘FORCE’ was more susceptible to singulation errors at higher operating speeds. For Field B, the indices of planting accuracy also revealed marked differences across CWD and planter speeds as shown in Table 4.2.

Table 4.2. In-row plant spacing metrics by closing wheel design (CWD) and planter speed in Field B, measured manually and calculated per ISO 7256/1-1984 standard with target spacing of 242.3 mm. Metrics: mean spacing, coefficient of variation (CV), Multiple index (< 121.15 mm), Miss index (> 363.45 mm), Quality of feed (121.15-363.45 mm), and Variability index. Different letters within columns indicate significant differences (Tukey's HSD, α = 0.05). Higher quality of feed index and lower miss/multiple indices indicate superior planting uniformity..

CWD	Planter speed (km h-1)	Multiple index (%)	Miss index (%)	Quality of feed index (%)
OEM	12	1.94 c	1.29 b	96.77 a
	16	1.70 c	3.66 a	94.66 b

CWD	Planter speed (km h-1)	Multiple index (%)	Miss index (%)	Quality of feed index (%)
SPIKES	12	0.77 d	3.87 a	95.34 a
	16	3.10 a	4.65 a	92.24 c
FORCE	12	3.78 a	2.27 b	93.93 b
	16	2.33 b	4.65 a	93.02 b
MAX	12	2.28 b	3.97 a	93.74 b
	16	0.58 d	3.53 a	95.88 a

In the second experimental site the 'OEM' system at 12 km h^{-1} demonstrated the highest quality of feed index (96.77%) and the lowest miss index (1.29%), indicating particularly efficient singulation under these conditions. Similarly, the 'MAX' device at 16 km h^{-1} achieved a high quality of feed index (95.88%) with the lowest multiple index (0.58%), reflecting minimal occurrence of both missed and double plantings. By contrast, the 'SPIKES' closing wheel at 16 km h^{-1} was associated with a higher multiple index (3.10%) and a reduction in feed quality (92.24%), suggesting a greater incidence of planting errors at increased ground speeds for this configuration. The 'FORCE' system exhibited relatively high multiple indices at both speeds (>2.3%) and moderate feed quality, which may indicate challenges in maintaining precise seed delivery under those settings. Overall, the results for Field B emphasize that both the furrow closing system and planter speed substantially modulate seed placement accuracy. Particularly, optimal performance—characterized by a high quality of feed index and minimal singulation errors—was observed with the 'OEM' and 'MAX' systems when operated at moderate speeds (12 or 16 km h^{-1}). In contrast, increased speeds typically resulted in marginal declines in planting precision for most CWD.

The analysis of miss index, double index, and quality of feed index across the two distinct fields revealed that planter speed and CWD significantly influenced singulation performance and plant spacing uniformity, following literature emphasizing the detrimental effects of increased planting speed on seed placement accuracy (Kuş, 2021; Nadin et al., 2019; Staggenborg et al., 2004). Consistent with prior results from (Ahmed et al., 2023; Badua et al.,

2018) slower planting speeds (12 km h^{-1}) generally resulted in lower miss and multiple indices and higher quality of feed values, reflecting more uniform seed singulation. However, exceptions were noted depending on the CWD and field, highlighting the complex interaction between planter speed, equipment configuration, and environment. For example, the 'SPIKES' and 'MAX' closing wheels delivered superior quality of feed indexes at both planter speeds in Field A, demonstrating that specific aftermarket designs may mitigate the negative impacts of increased operational velocity, a phenomenon suggested by Li et al. (2015) and Drewry et al. (2020) to derive from improved seed-to-soil contact and residue management. Further conclusions could be extracted from the precision index and CV for each planter speed and CWD treatment, which are summarized in Figures 4.4 and 4.5 for Field A and Field B, respectively.

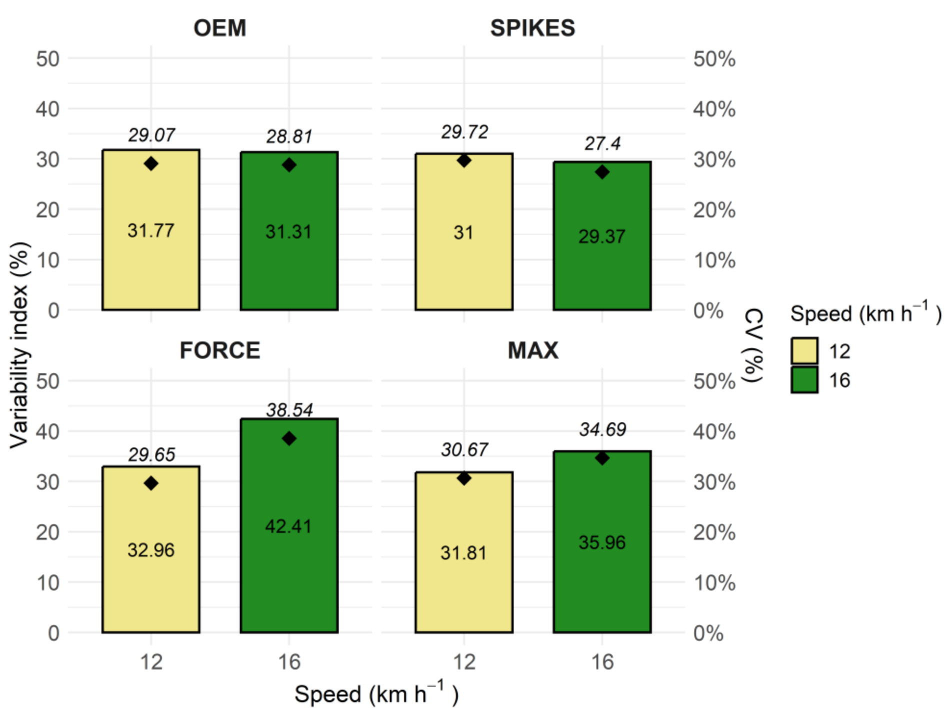

Figure 4.4. Variability index (bars with center labels) and coefficient of variation (diamonds, italic labels) for plant spacing by planter speed (12, 16 km h^{-1}) and closing wheel design (OEM, SPIKES, FORCE, MAX) in Field A.

In Field A (Figure 4.4), ‘FORCE’ at 16 km h^{-1} exhibited the highest variability index value (42.41%), indicating greater variability and therefore poorer spacing uniformity, following the concept proposed by Kachman & Smith (1995) if a higher value of the variability index indicates greater spacing variability, despite simultaneously recording the highest CV (38.54%). Conversely, the ‘SPIKES’ device at 16 km h^{-1} showed the lowest variability index (27.4%) and a comparatively lower CV, reflecting more consistent and uniform plant spacing. Across treatments in Field A, lower variability index values—a marker of better performance—were generally associated with lower CV values, although variability remained moderate to high.

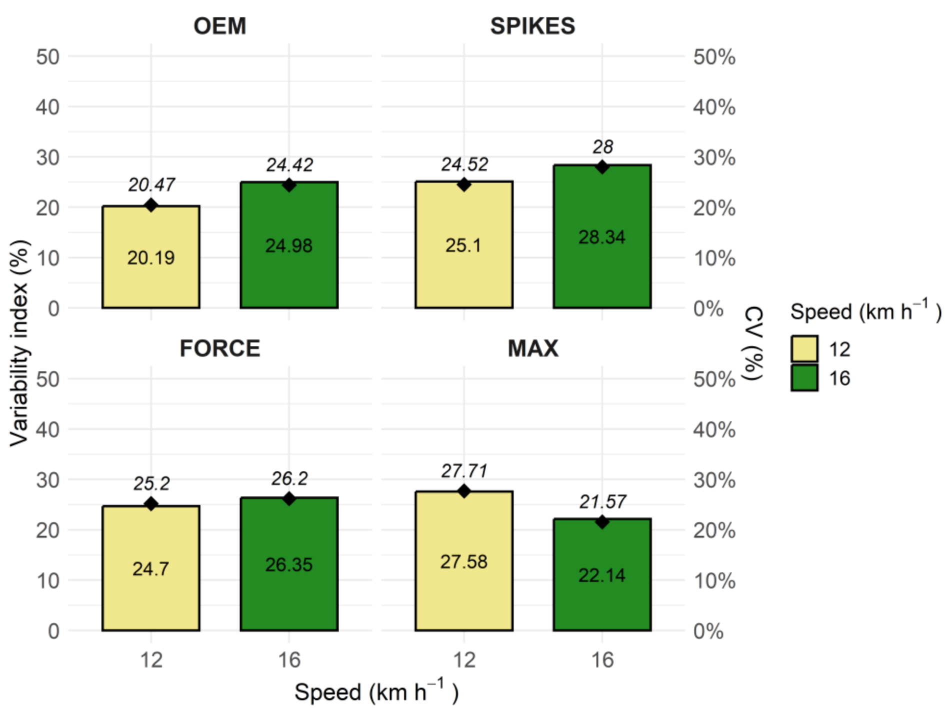

Figure 4.5. Variability index (bars with center labels) and coefficient of variation (diamonds, italic labels) for plant spacing by planter speed (12, 16 km h^{-1}) and closing wheel design (OEM, SPIKES, FORCE, MAX) in Field B.

In Field B (Figure 4.5), variability index values were lower overall—indicative of better spacing uniformity—ranging from 20.19% (‘OEM’, 12 km h^{-1}) to 28.34% (‘SPIKES’, 16 km h^{-1}). CV values in Field B were also consistently lower than those observed in Field A, with the 'MAX' device at 16 km h^{-1} achieving the best combination of low variability index (22.14%) and low CV (21.57%), demonstrating a high degree of plant spacing uniformity. These contrasting metrics between fields emphasize the influence of site conditions on the interaction between equipment settings and seed placement consistency. Variability index and CV results provided further insights into spacing uniformity. The 'FORCE' system exhibited the highest variability index values at 16 km h^{-1} in Field A, indicating greater variability and thus poorer uniformity, which was consistent with the most significant CV values (>38%). This distinction highlights the difference between overall seed placement precision and spatial consistency within the stand. These findings agree with previous research showing that increased planting speeds often elevate plant spacing variability even when average precision appears acceptable (Liu et al., 2017; Moody et al., 2003). In Field B, generally lower precision indices coincided with reduced CV values, suggesting that local soil properties and crop residue influence the interaction between mechanical planter settings and seed placement uniformity, supporting earlier observations on the importance of soil load and residue type (Doan et al., 2005; Hanna et al., 2010). The differential effect of planter speed among fields and CWD types underlines the need for site-specific planter calibration. This aligns with Ferreira et al. (2019)recommendations that advocate tailored adjustments to CWD, along with other factors like downforce and seed metering units, to improve stand establishment. While faster speeds are commonly associated with increased missed and double seeds (Garcia et al., 2006; Nielsen, 1995), some CWD, especially aftermarket closing wheels, demonstrated a capacity to maintain or even improve placement accuracy under elevated speed conditions, offering a promising avenue toward balancing operational efficiency and planting precision.

4.4.2 Seed depth response

The depth at which corn seeds are planted is critical to stand establishment and ultimate productivity. In this study, average seed depths were evaluated across various combinations of planter speed and CWD in two distinct experimental fields. Figures 4.6 and 4.7 illustrate these mean seed depth values for Field A and Field B, respectively, highlighting significant differences in planter operational speed and CWD type in each environment. In Field A (Figure 4.6), at a planter speed of 12 km h^{-1}, all treatments had a clear tendency to significantly exceed the seed depth set on the equipment regulation of 50.8 mm. When the planter speed was increased to 16 km h^{-1}, the average seed depth approached to 50.8 mm for all CWD treatments except ‘SPIKES’, which did not show significant differences between speeds; in this case, both mean depths remained deeper than 50.8 mm. This pattern indicates that, for most CWD evaluated, using a higher planter speed in Field A generally reduced the excessive depth at the lower speed, bringing seed placement closer to the intended depth value. However, the ‘SPIKES’ design appeared less sensitive to speed changes, consistently resulting in deeper seed placement. The observed variation in depth depending on treatment and speed aligns with previous reports showing that planter operating speed affects depth uniformity and the overall mean depth achieved in the field (Kuş, 2021; Nadin et al., 2019; Staggenborg et al., 2004). While lower speeds are often associated with more consistent seed depth placement (Ahmed et al., 2023; Badua et al., 2018), the present results from Field A suggest that fast forward speeds may also reduce excessive depth under certain conditions, depending on the CWD employed. This supports the view that the mechanical interaction between depth control components, CWD, and soil conditions modulates how operating speed translates into final seed placement (Ahmed et al. 2023; Virk et al. 2020). From a physiological perspective, planting too deep can delay emergence by increasing the thermal time required for seedlings to reach the surface (Gupta et al., 1988). Although some degree of crop compensation may occur when depth uniformity is suboptimal (Stewart et al., 2021), deviations from the optimal range—either too shallow or too deep—have been shown to influence emergence uniformity negatively and, in certain contexts, yield potential (Sassenrath et al., 2020).

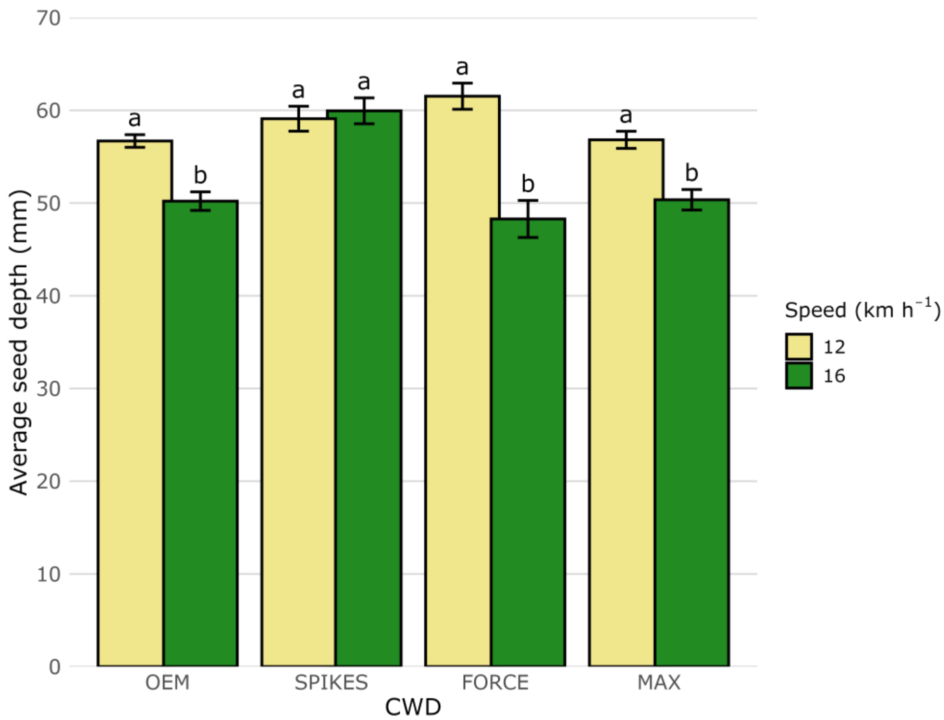

Figure 4.6. Average seed depth (mm) as affected by planter speed (12 and 16 km h⁻¹) and closing wheel design (CWD) treatments in Field A. Error bars represent 95% confidence intervals. CWD treatments include: OEM (original standard round rubber wheel for equipment manufacturer), SPIKES (twisted spiked closing wheels), FORCE (FurrowForce® system), and MAX (Furrow Max™ system). Lowercase letters indicate significant differences between treatment groups (Tukey's HSD test, α = 0.05).

Conversely, Field B (Figure 4.7) showed a somewhat different response pattern. Some CWD treatments ('OEM' and 'MAX') had slightly deeper average seed depths at higher speeds, while others ('SPIKES' and 'FORCE') exhibited either minor or opposite trends. Additionally, statistical groupings suggest less noticeable differences among treatments in Field B, indicating that site-specific soil and environmental conditions influence the effect of speed and CWD on seed depth control.

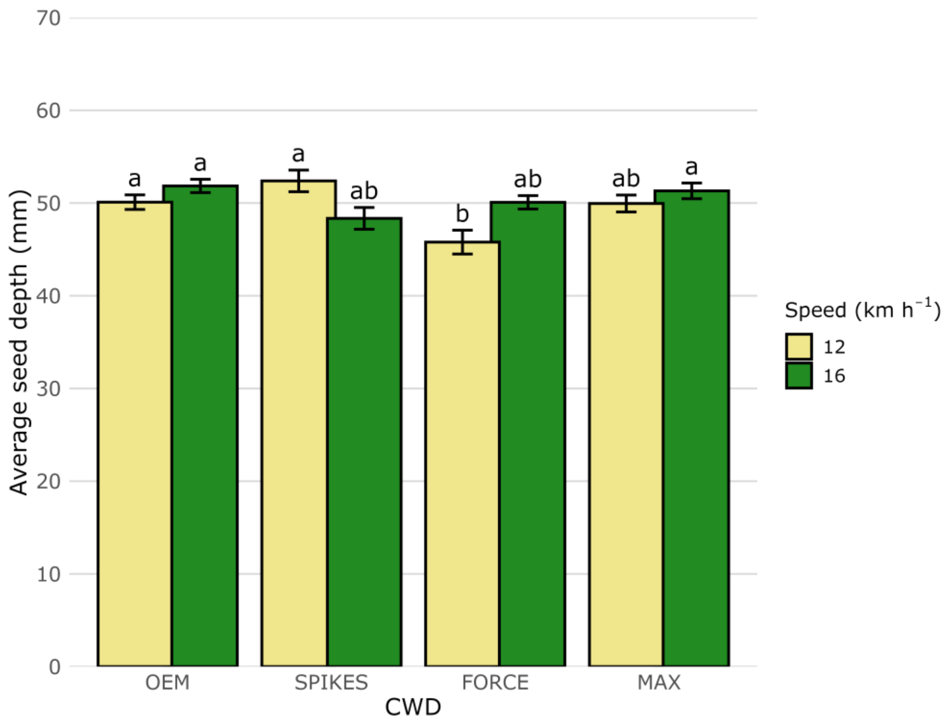

Figure 4.7. Average seed depth (mm) as affected by planter speed (12 and 16 km h^{-1}) and closing wheel design (CWD) treatments in Field B. Error bars represent 95% confidence intervals. CWD treatments include: OEM (original standard round rubber wheel for equipment manufacturer), SPIKES (twisted spiked closing wheels), FORCE (FurrowForce® system), and MAX (Furrow Max™ system). Lowercase letters indicate significant differences between treatment groups (Tukey's HSD test, α = 0.05).

Notably, the soil moisture levels recorded in Field A were higher and more consistent than those in Field B (Figure 4.1), which showed lower and more variable moisture conditions. Depending on the experiment field, this difference likely affected the planter's ability to maintain target seed depths. The higher soil moisture in Field A may have enabled more aggressive disk penetration and resulted in less uniform seed placement at various speeds. In contrast, the reduced soil moisture in Field B could have intensified mechanical resistance to penetration and soil-planter interactions, leading to different seed depth responses depicted in Figure 4.7. The observed seed depth responses to planter speed and CWD displayed distinct patterns between the two experimental fields, underscoring the complex interactions between mechanical and environmental factors influencing seed placement. In contrast to results from Field A, Field B exhibited greater sensitivity to speed and CWD treatments, with 'OEM' and 'MAX' showing significant reductions in seed depth at higher speeds. At the same time, 'SPIKES' maintained deeper and more uniform placement.

The current behavior of the 'SPIKES' treatment in Field A, with seed depths consistently exceeding 50.8 mm regardless of planter speed, underscores the need to adjust the CWD and operational parameters to attain optimal planting depths within a TSDR as established in previous studies (Sassenrath et al., 2020; Stewart et al., 2021). These disparities between treatments and fields highlight how site-specific factors, such as soil moisture and texture, can significantly modulate the interaction between planter speed and CWD effectiveness in consistently placing seeds within the TSDR (Gupta et al., 1988; Morrison & Gerik, 1985). Collectively, these results emphasize the importance of tailoring both planter settings (such as forward speed), and CWD selection to field conditions to maximize seed depth uniformity and placement quality, as substantiated by recent mechanization research (Ahmed et al., 2023; Drewry et al., 2020; Lu et al., 2024). To better quantify this relationship, the results for η (representing the probability of sowing within the TSDR for each field, η_A and $\eta_{B,}$ respectively) are shown in Tables 3 and 4. Statistical analyses revealed significant main effects of both planter speed ($p<0.05$) and CWD type ($p<0.05$) for seeds sown in Field A, but not in Field B, demonstrating that each factor independently influences the probability of reaching the TSDR and that the particular conditions of each site highly modulate this influence. The interaction was also site-dependent, being significant in Field A but not in Field B, suggesting that the specific

CWD and the environment modulate the effect of speed on the probability of sowing within the TSDR.

For most CWD, increasing planter speed from 12 km h⁻¹ to 16 km h⁻¹ showed a modest tendency to increase the probability of seeds being placed within the TSDR in Field A (Table 4.3), though this effect was not statistically significant at the 5% level (Field A: $\beta = 0.575$, $p = 0.110$; Field B: $\beta = -0.116$, $p = 0.632$). In Field A, 'MAX' presented a significantly higher likelihood of optimal seed placement compared to 'OEM' ($\beta = 0.866$, $p = 0.017$), whereas 'FORCE' was associated with a significantly lower probability ($\beta = -0.833$, $p = 0.033$), a trend not observed in Field B (Table 4.4), where effects of CWD were minor and not significant ($p > 0.05$ for all main effects). Notably, in Field A, 'SPIKES' showed no significant difference from 'OEM' at 12 km h^{-1} ($\beta = -0.452$, $p = 0.219$), but at higher speed, the significant negative interaction ($\beta = -1.163$, $p = 0.033$) indicated that the probability of TSDR placement with 'SPIKES' was further reduced at 16 km h^{-1} relative to the reference, a pattern not mirrored in Field B (interaction $\beta = 0.344$, $p = 0.423$). These contrasting results across fields highlight the influence of context-specific factors such as soil moisture (Figure 4.1) and texture, which may have diminished the magnitude and significance of CWD-related effects in Field B.

Table 4.3. Binary logistic regression for seed placement probability within target seed depth range (TSDR: 44.5-57.1 mm, target 50.8 mm) by planter speed and closing wheel design (CWD) in Field A. Reference: 12 km h^{-1}, OEM. MAX increased target depth odds (OR = 2.38, $p < 0.05$), FORCE decreased odds (OR = 0.43). Significant speed × SPIKES interaction (OR = 0.31, $p < 0.05$). OR = odds ratio; CI = 95% confidence interval.

Variable	Identification	Value of β	Standard Error	z-value	p-value	[1] OR (95% CI)
Intercept	β0	-0.29	0.25	-1.13	0.26	0.75 (0.43-1.23)
16 km h^{-1}	β1	0.58	0.36	1.60	0.11	1.78 (0.88-3.63)
'SPIKES'	β2	-0.45	0.37	-1.23	0.22	0.64 (0.31-1.30)
'FORCE'	β3	-0.83	0.39	-2.13	<0.05	0.43 (0.20-0.93)
'MAX'	β4	0.87	0.36	2.38	<0.05	2.38 (1.17-4.91)
16 km h^{-1} * 'SPIKES'	β5	-1.16	0.55	-2.13	<0.05	0.31 (0.11-0.90)
16 km h^{-1} * 'FORCE'	β6	-0.20	0.54	-0.37	0.71	0.82 (0.28-2.39)
16 km h^{-1} * 'MAX'	β7	-0.62	0.51	-1.20	0.23	0.54 (0.20-1.47)

Variable	Identification	Value of β	Standard Error	z-value	p-value	[1] OR (95% CI)

Note: The dependent variable, seed depth, was coded as 1 = seeds within the depth range of 44.5 to 57.1 mm, and 0 = seeds outside this range. Reference categories are: Planter speed = 12 km h^{-1}, CWD = 'OEM'. Odds ratios (OR) are calculated as exp(β). An OR less than 1 indicates a lower likelihood of placing seeds within the depth range of 44.5 to 57.1 mm compared to the reference category. Conversely, an OR greater than 1 indicates a higher probability.

Technically, these findings underscore how operational adjustments—such as planter speed and CWD selection—can have differential impacts depending on the environmental setting. In both fields, the tendency to achieve suboptimal (too deep or too variable) seed placement at 12 km h^{-1} for several CWD treatments suggests that the downforce regulation (via "T" handle position or pneumatic settings) may not have been adequately optimized, especially under the specific mechanical and soil conditions encountered. Improved depth placement at the higher speed (16 km h^{-1}) for some systems, including 'OEM', 'FORCE', and 'MAX', in Field A likely reflects a partial compensation for excessive initial depth and implies possible advantages in refining planting capacity and seed depth precision at increased speeds; however, these potential operational benefits must be evaluated alongside possible effects on emergence uniformity and final stand density.

Table 4.4. Binary logistic regression for seed placement probability within target seed depth range (TSDR: 44.5-57.1 mm, target 50.8 mm) by planter speed and closing wheel design (CWD) in Field B. Reference: 12 km h^{-1}, OEM. MAX increased target depth odds (OR = 2.38, $p < 0.05$), FORCE decreased odds (OR = 0.43). Significant speed × SPIKES interaction (OR = 0.31, $p < 0.05$). OR = odds ratio; CI = 95% confidence interval.

Variable	Identification	Value of β	Standard Error	z-value	p-value	[1] OR (95% CI)
Intercept	β0	0.19	0.16	1.20	0.23	1.21 (0.89-1.67)
16 km h^{-1}	β1	-0.12	0.24	-0.48	0.63	0.89 (0.56-1.43)
'SPIKES'	β2	-0.16	0.30	-0.55	0.58	0.85 (0.47-1.52)
'FORCE'	β3	0.11	0.30	0.37	0.71	1.12 (0.72-2.07)
'MAX'	β4	0.19	0.27	0.71	0.48	1.21 (0.72-2.07)
16 km h^{-1} * 'SPIKES'	β5	0.34	0.43	0.80	0.42	1.41 (0.61-3.29)
16 km h^{-1} * 'FORCE'	β6	0.67	0.44	1.52	0.13	1.96 (0.83-4.68)
16 km h^{-1} * 'MAX'	β7	-0.13	0.39	-0.32	0.74	0.88 (0.41-1.89)

Note: The dependent variable, seed depth, was coded as 1 = seeds within the depth range of 44.5 to 57.1 mm, and 0 = seeds outside this range. Reference categories are: Planter speed = 12 km h-1, CWD = 'OEM'. Odds ratios (OR) are calculated as exp(β). An OR less than 1 indicates a lower likelihood of placing seeds within the depth range of 44.5 to 57.1 mm compared to the reference category. Conversely, an OR greater than 1 indicates a higher probability.

Of particular note, ‘SPIKES’ wheels tended to move seed placement deeper than the TSDR at both speeds and in both fields, a result possibly linked to altered furrow architecture or excessive mechanical load imposed by their configuration. These findings suggest the need for tailored mechanical regulation—such as lighter downforce settings or adjustments in the relative angle of the star wheels—when using ‘SPIKES’ in similar soil conditions, deviating from the configurations applied in the present study. Collectively, these results corroborate prior work emphasizing that the interaction between planter speed, CWD type, and environmental factors is critical for consistent, optimal seed placement, and highlight the importance of site-specific equipment calibration (Ahmed et al., 2023; Kuş, 2021; Virk et al., 2020).

The modeled probability of achieving the TSDR across both fields, shown in Figures 4.8 and 4.9, demonstrates important contrasts in CWD performance and responsiveness to planter speed. In Field A (Figure 4.8), the ‘MAX’ system consistently provided the highest probability of seeds being placed within the TSDR, remaining above 63% for both speeds. The ‘OEM’ and ‘FORCE’ treatments showed improvement with increased speed: ‘OEM’ rose from 42.9% at 12 km h^{-1} to 57.1% at 16 km h^{-1}, and ‘FORCE’ increased from 24.6% to 32.2%. ‘SPIKES’ performed the worst, with probability dropping from 32.3% at 12 km h^{-1} to just 21.0% at 16 km h^{-1}, signaling low overall effectiveness and susceptibility to placement errors at higher speeds.

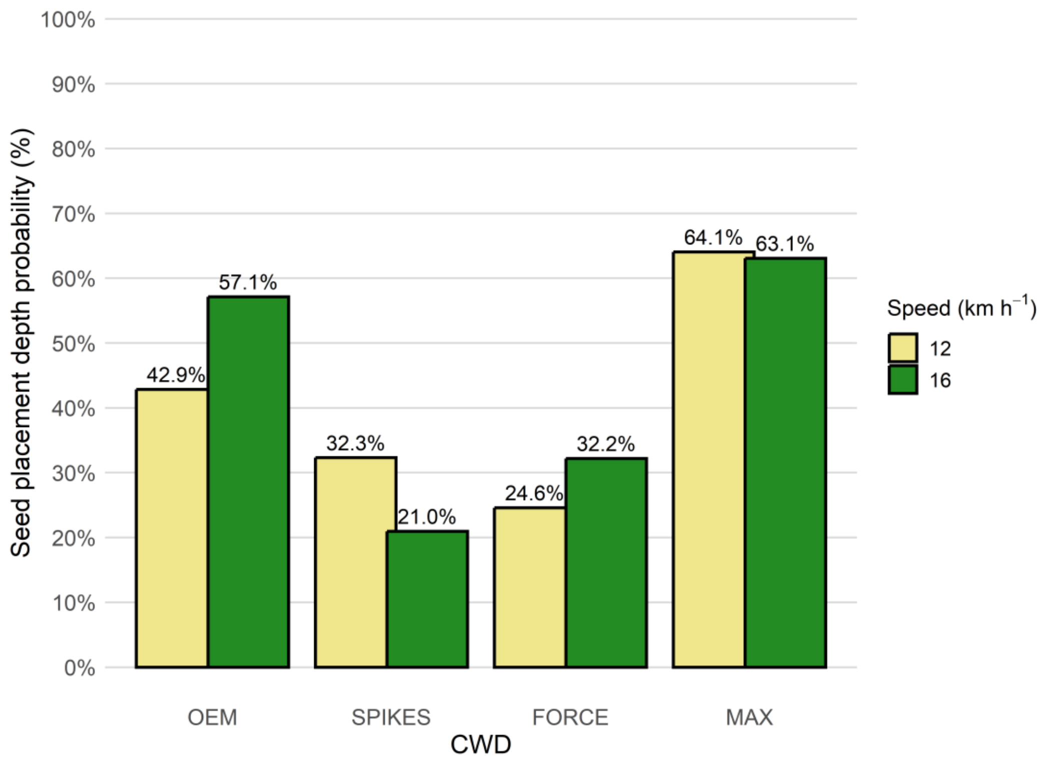

Figure 4.8. Predicted probability of seed placement within target seed depth range (TSDR: 44.5-57.1 mm, target 50.8 mm) by closing wheel design (CWD) and planter speed in Field A. MAX achieved the highest probability (~64%), while SPIKES and FORCE showed the lowest (21-32%). Probabilities derived from logistic regression (Table 4.3).

By contrast, Field B (Figure 4.9) exhibited substantially different patterns. All treatments in Field B achieved probabilities within a narrow range (50–70%), with 'FORCE' displaying the highest values at both speeds (54.8% at 12 km h^{-1}, rising to 70.3% at 16 km h^{-1}). 'MAX' and 'SPIKES' had similar modeled probabilities (53–60%), with little effect of speed, while 'OEM' showed a slight decline when speed was increased (54.8% to 52.0%). Unlike Field A, in Field B the 'FORCE' design outperformed others at high speed, suggesting an improved ability to maintain depth placement under more challenging or variable soil conditions. Additionally, the narrower spread of probabilities in Field B highlights that site conditions can moderate the impact of CWD and speed interactions, likely by influencing furrow closure mechanics, soil resistance, and seed-soil contact effectiveness.

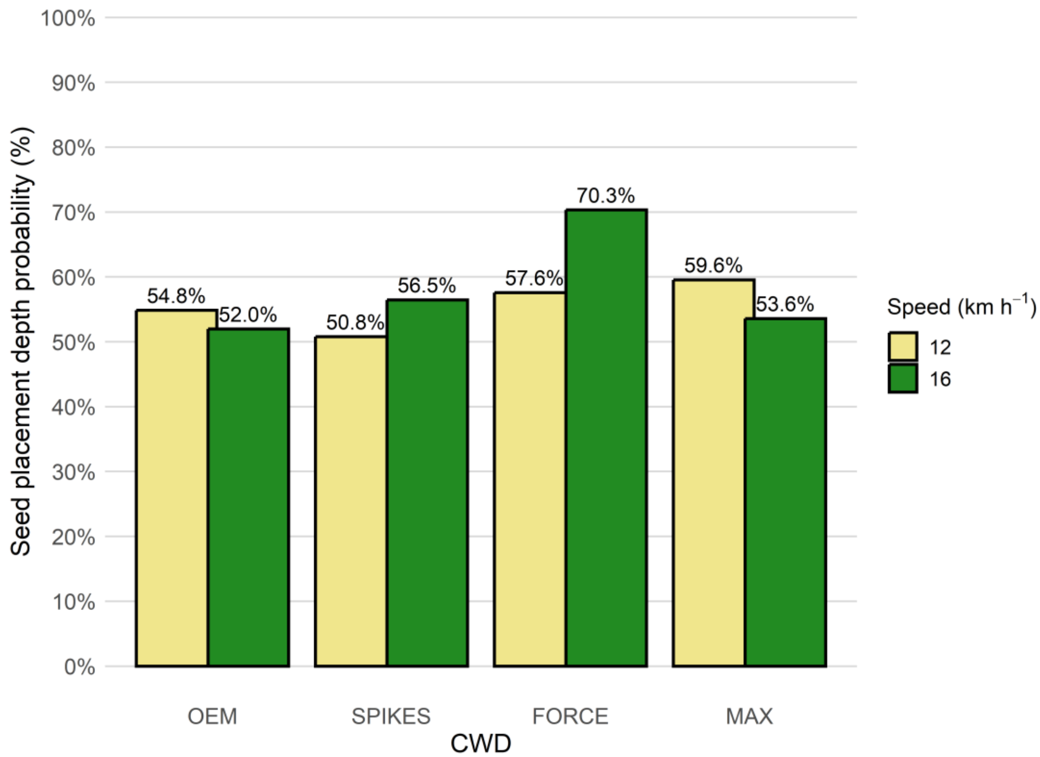

Figure 4.9. Predicted probability of seed placement within target seed depth range (TSDR: 44.5-57.1 mm, target 50.8 mm) by closing wheel design (CWD) and planter speed in Field B. FORCE achieved the highest probability at 16 km h^{-1} (70.3%). Field B showed more uniform performance (50-70%) across CWD treatments than Field A. Probabilities derived from logistic regression (Table 4.4).

These results confirm that maximizing placement probability in the TSDR depends on selecting CWD and planter speed suited to the specific field environment. While ‘MAX’ consistently excelled in Field A regardless of speed, in Field B, the ‘FORCE’ system clearly benefited from higher speed. The poor and declining effectiveness of ‘SPIKES’ in Field A at increased speed contrasts with Field B where its performance closely tracked that of ‘MAX,’ underscoring that mechanical adaptation (geometry, load, vibration sensitivity) interacts with soil conditions to determine placement uniformity (Lu et al., 2024; Morrison & Gerik, 1985).

Overall, careful matching of equipment configuration to field context is required for reliable seed placement in corn. The combined evidence from the regression model (η) and the predicted probabilities illustrated in Figures 4.8 and 4.9 underscores the importance of optimizing planter speed and closing wheel selection to achieve target seed depth reliably. This precision in seed placement is directly linked to uniform emergence. It can have significant implications for yield potential, as noted by Sassenrath et al. (2020) and Stewart et al. (2021), and can be seen reflected in our own results of IEDW in Figure 4.10.

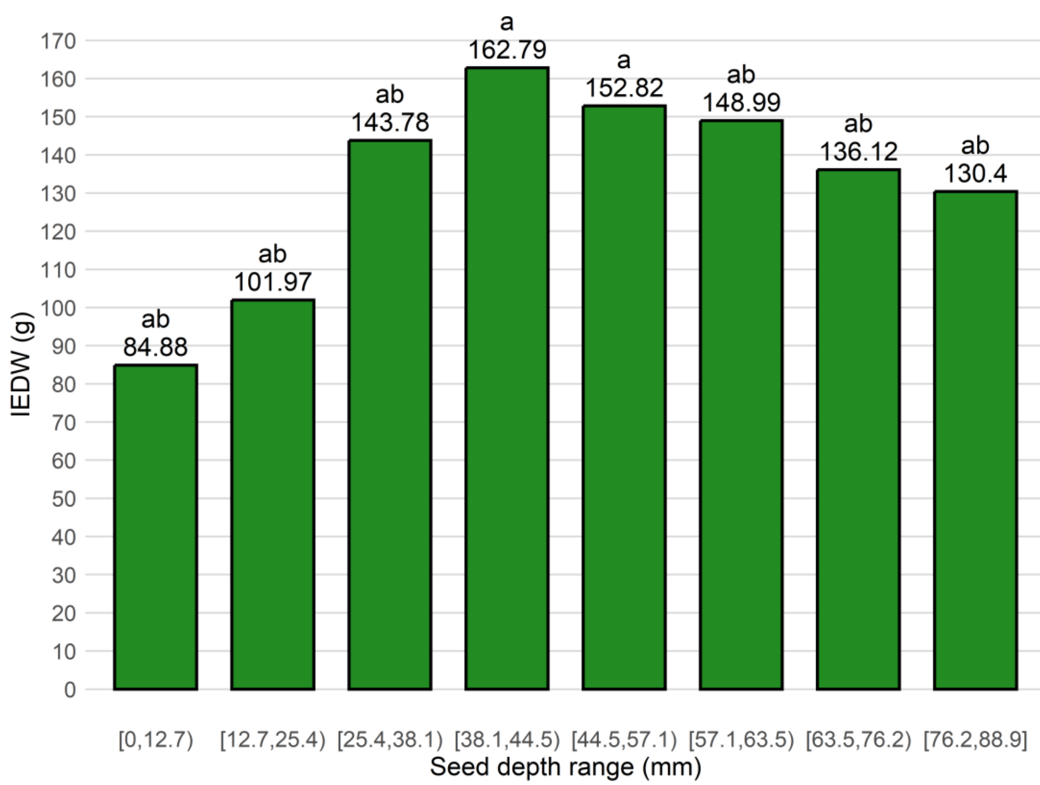

Figure 4.10. Mean grain dry weight per ear (IEDW) by seed depth range, combining both fields and all treatments. Seed depth ranges closest to the 50.8 mm target [38.1-44.5 mm and 44.5-57.1 mm] produced the highest yields (~163 and ~153 g ear^{-1}). Very shallow or deep placement reduced grain production. Different letters indicate significant differences (Tukey's HSD, α = 0.05)..

Figure 4.10 shows the mean IEDW for plants established from seeds sown at different depth ranges in both experimental fields. The highest IEDW was observed for seeds placed within the 38.1–44.5 mm range (162.8 g), closely followed by the target depth (44.5–57.1 mm) range (152.8 g). Shallower placements (0–25.4 mm) were associated with noticeably lower ear weights, while deeper placements beyond 63.5 mm also reduced IEDW. Statistical grouping letters indicate that the two depth ranges from approximately 38 mm to 57 mm were not significantly different. Still, both surpassed most other depth categories in ear weight. These findings provide empirical support to the concept of an agronomic optimum for seed depth, with significantly more positive results in seeds sown in a slightly shallower range of depth for these experimental fields, than the 50–76 mm target depth interval proposed by Sassenrath et al. (2020) and Stewart et al. (2021). Planting too shallow likely restricts early root development and water access. At the same time, excessively deep placement can delay emergence (Gupta et al., 1988) and reduce early vigor, contributing to lower potential ear mass. The observed peak in IEDW for depths just over the TSDR may also reflect favorable soil thermal and moisture conditions in that depth range for the specific environment of these experimental fields, allowing slightly shallower placements within the mid-range to perform equally well. This becomes clearer if the same results are observed but with a different interval around the target depth, changing from a 6.35 mm (44.5-57.1 mm) to a 12.70 mm distance (38.1-63.5 mm), as shown in Figure 4.11.

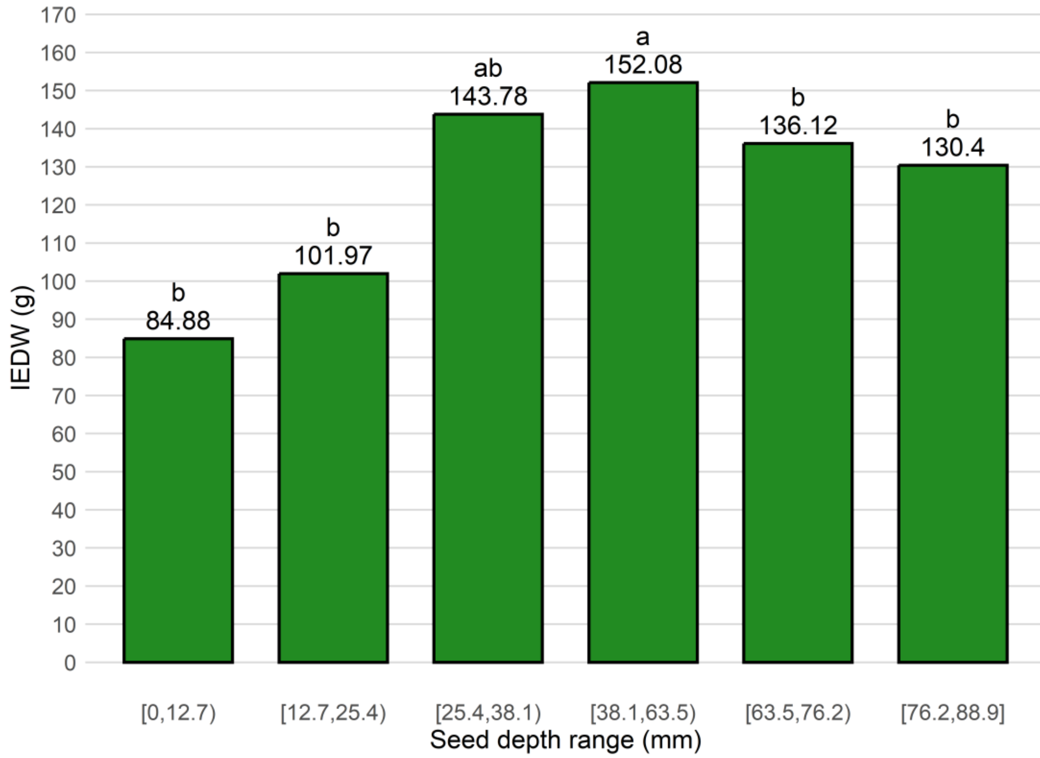

Figure 4.11. Mean grain dry weight per ear (IEDW) by seed depth range, combining both fields and all treatments. The central range [38.1-63.5 mm] encompassing target depth (50.8 mm ± 12.7 mm) produced highest yield (152.08 g ear^{-1}). Shallow (<25.4 mm) or deep (>63.5 mm) placement significantly reduced grain production. Different letters indicate significant differences (Tukey's HSD, α = 0.05).

Figure 4.11 shows that if the depth range around the target depth is expanded by using an interval of 12.70 mm above and below the target depth, it contains the seedlings that produced the heaviest ears in the experiment. However, from a practical standpoint of regulating planting equipment, observing a 12.70 mm distance with the target depth chosen in each field would be a good reason to adjust the row unit components during the planter's setup in the field. Overall, the relationship between seed depth and IEDW shown in Figures 4.10 and 4.11 reinforces that precise control of seed placement within an optimal depth window is agronomically critical for uniform emergence and maximizing potential grain yield at the plant level. These results connect the mechanical aspects of planting—examined earlier in terms of speed and closing wheel effects—to tangible yield components, strengthening the case for planter adjustments that keep seed depth within the agronomic optimum.

4.4.3 Percentage of target population achieved

The live plant population is a widely recognized parameter for evaluating planter performance in corn crops (Haarhoff & Swanepoel, 2018). Following full emergence declaration in the strips, PTPA was calculated for each experimental site, with results presented in Figures 4.12 and 4.13. In Field A (Figure 4.12), a significant reduction in PTPA was observed for the 'SPIKES' and 'FORCE' CWD treatments at the higher planter speed of 16 km h^{-1}. This reduction corresponds closely with the elevated Miss Index values of 8.06% and 10.17%, respectively, recorded at this speed. Moreover, 'FORCE' exhibited the highest Multiple Index (3.39%) and the lowest Quality of Feed Index (86.44%) at 16 km h^{-1}, directly impacting the PTPA, which dropped to 83.7% for this treatment combination used in this site.

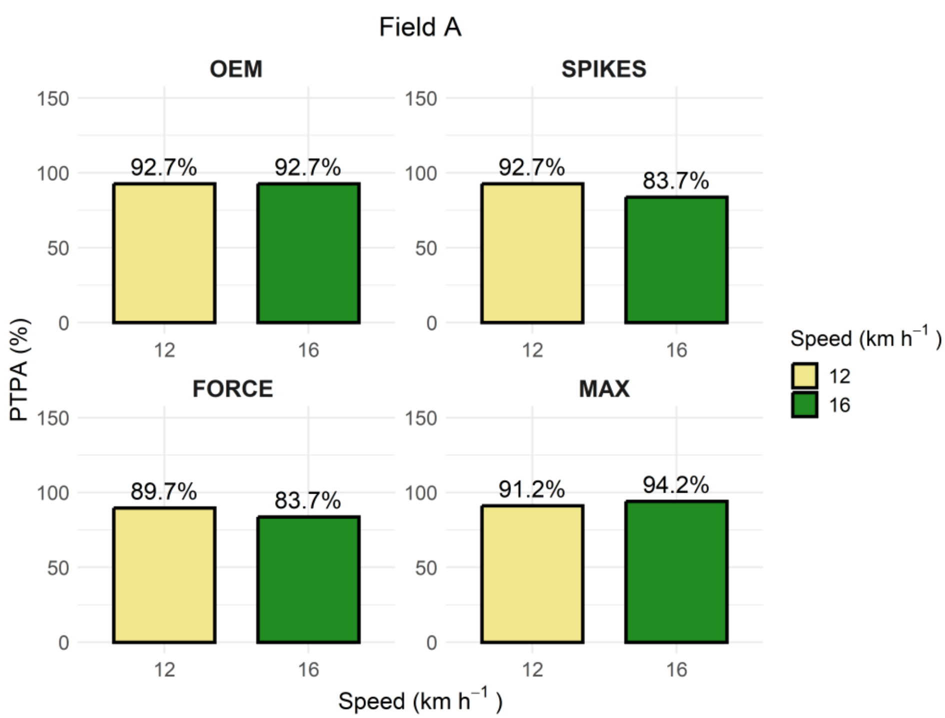

Figure 4.12. Percentage of target plant population achieved (PTPA) by closing wheel design (CWD) and planter speed in Field A (target: 54,869 plants ha^{-1}). All treatments

achieved >83% of the target population. OEM and MAX maintained consistent performance (~91-94%) across speeds, while SPIKES decreased slightly at higher speeds (83.7%).

These findings align with established literature emphasizing the critical role of seed placement precision in achieving a higher live plant population and yield in corn (Sassenrath et al., 2020; Stewart et al., 2021). Operating at higher planter speeds negatively impacted seed depth consistency and spacing uniformity in Field A, increasing the likelihood of missed and double seeds (Kuş, 2021; Nadin et al., 2019). In Field B (Figure 4.13), PTPA values remained generally higher across treatments, with less pronounced speed-related reductions, reflecting potentially more favorable surface and residue conditions that reduce operational constraints. The 'OEM' system achieved the highest PTPA at 12 km h^{-1} (97.6%), supporting prior conclusions on the benefits of moderate speeds and specific closing wheel designs for maintaining singulation accuracy and emergence uniformity.

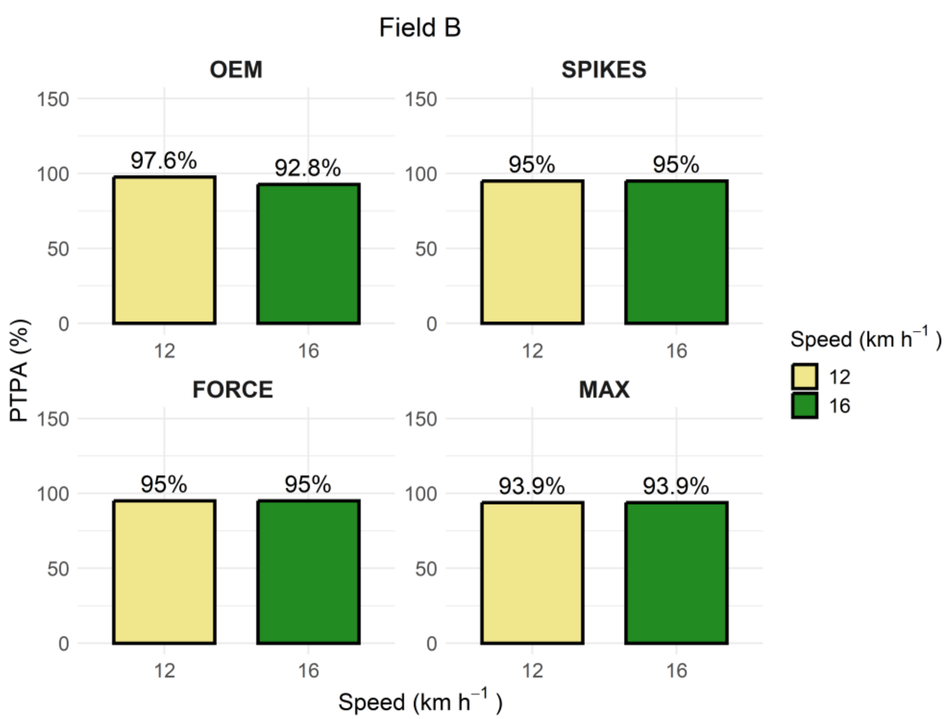

Figure 4.13. Percentage of target plant population achieved (PTPA) by closing wheel design (CWD) and speed in Field B (target: 54,375 plants ha^{-1}). All treatments achieved >92% of the target population, showing more uniform performance than Field A. SPIKES and FORCE maintained 95% across both speeds, while OEM decreased slightly at higher speeds (92.8%).

Overall, the observed declines in PTPA with increased planter speed—most notable in treatments with higher miss and multiple indices—underscore the interconnectedness of seed placement accuracy, planting depth uniformity, and final plant population. These outcomes reinforce the need for site-specific planter calibration, including tailored closing wheel selections and planter speed adjustments, to optimize plant stand establishment and ultimately maximize yield potential in corn cropping systems. The data also confirm previous findings on the detrimental effect of excessive operating speeds and the mitigating potential of innovative closing wheel designs to preserve seed placement quality under challenging field conditions (Drewry et al., 2020; Y. Li, Xiantao, et al., 2015).

4.4.4 Discussion of uncertainty and methodological limitations

Although the methodologies used to measure seed depth, live plant population, and grain yield per plant provide robust data for assessing planter performance, several inherent limitations and sources of uncertainty should be recognized. The manual seed depth measurement assumes that the wooden marker accurately replicates gauge wheel pressure and that the soil surface is sufficiently level for consistent vertical measurements. Still, variability in soil clods, residue, and operator technique can introduce errors. Similarly, the live plant population count relies on the assumption of complete and accurate seedling identification at 100% emergence, ignoring possible late emergence or early mortality, and may not capture intra-plot spatial variability comprehensively. Grain yield per plant measurements assumes uniform shelling efficiency and representative moisture sampling from pooled kernels; however, within-ear moisture and kernel density variation, as well as sampling biases, can affect dry weight accuracy. Furthermore, operational variables such as increased planter speed and various closing wheel designs impact seed placement precision, which in turn influences data variability seen across experimental sites and treatments.

These methodological limitations create uncertainty when interpreting treatment effects, especially when small differences in stand establishment or yield components are reported. Notably, environmental variability across sites adds factors beyond the planting equipment settings, making it harder to identify causal effects. Acknowledging these limitations underscores the importance of repeated measurements, testing across varied soil and climate conditions, and using complementary methods such as sensor-based real-time data collection to improve confidence in future evaluations of planter technology performance.

4.5 Conclusions

This study demonstrates that planter speed and CWD significantly influence seed placement accuracy, plant spacing uniformity, and live plant population in corn. The ‘MAX’ and ‘SPIKES’ systems consistently achieved superior feed quality indices and reduced singulation errors across a range of planter speeds, indicating that certain CWD can partially offset the typical adverse effects of increased planter speeds, particularly observed in Field A. Conversely, the ‘FORCE’ system was notably more susceptible to increased double and missed seed rates at higher speeds, leading to poorer spatial uniformity and potentially compromised live plant establishment. Field B further highlighted the interplay between CWD and planter speed, with the ‘OEM’ system at 12 $km\ h^{-1}$ and the ‘MAX’ system at 16 $km\ h^{-1}$ producing optimal outcomes. Analysis of in-row plant spacing indices and coefficients of variation confirmed the general trend that higher planter speeds increase spacing variability; however, specific aftermarket CWDs showed the ability to maintain spacing uniformity even under these challenging operational scenarios. This reinforces the importance of tailored, site-specific planter calibrations, encompassing closing wheel selection and speed optimization, to achieve consistent and productive stand establishment.

Regarding seed placement depth, planter speed and CWD were found to critically affect the probability of achieving optimal seed depth distribution, with local soil and environmental conditions strongly modulating these effects. In Field A, the ‘MAX’ closing wheel consistently delivered high probabilities of optimal seed depth regardless of speed, while ‘OEM’ and ‘FORCE’ performance improved at higher speeds. The ‘SPIKES’ design was less effective at elevated speeds, emphasizing the necessity of matching closing wheel geometry and planter setup to field conditions to minimize depth placement errors. In Field B, a narrower range of depth probabilities was observed across treatments, with the ‘FORCE’ system showing particularly strong performance at higher speeds, reflecting the pivotal influence of soil moisture and surface conditions on seed placement mechanics. From an agronomic perspective, our results reinforce the critical importance of planting depth precision. Seeds placed within an intermediate depth range (~38–63.5 mm) produced substantially heavier ears, aligning with previously reported optimal depth windows (TSDR), and highlighting the linkage between precise mechanical control of seed placement and biological yield outcomes. These findings advocate for carefully calibrating operating speed and closing wheel design to consistently achieve seed placement within the optimal depth zone, thereby improving emergence uniformity and maximizing yield potential.

Finally, the PTPA further confirmed the central role of planter speed and CWD in determining successful live plant population. Higher speeds (16 km h^{-1}) significantly reduced

PTPA for ‘SPIKES’ and ‘FORCE’ treatments in Field A, corresponding to elevated miss and multiple seed indices and reduced singulation uniformity. In contrast, the ‘OEM’ and ‘MAX’ systems maintained populations closer to target levels even at increased speeds, demonstrating superior ability to preserve seed feed quality and spatial placement precision. These results highlight the necessity of integrating site-specific equipment selection and speed management to optimize final plant populations—key determinants of corn yield and profitability.

Overall, this study underscores the importance of selecting and calibrating planter mechanical components in concert with environmental conditions to enhance stand uniformity, crop establishment, and production efficiency in modern precision agriculture.

Chapter 5 - Adaptive dual hydraulic force control: linking soil variability, mechanical loads, and stand uniformity in precision planting

5.1 Abstract

Dual-force hydraulic regulation offers a promising approach for adaptive control of planter row-unit forces in precision agriculture. This study evaluated a prototype dual hydraulic system capable of real-time modulation of uplift and downforce pressures in response to spatial soil variability and operational setpoints. Field experiments were conducted in 2025 in northcentral Kansas, USA, using a split-plot design with two planter speeds (8.9 and 11.3 km h^{-1}) and three downforce margin levels (445, 778, and 1112 N) applied in randomized subplots. A John Deere 1775NT planter equipped with a prototype of dual-force hydraulic force was used with a custom data acquisition system, which included real-time hydraulic pressure, gauge wheel load (GWL), opening disk load (ODL), and high-accuracy GPS, all sampled at 10 Hz. Post-planting assessments measured seedling emergence and in-row plant spacing using standardized indices. Results demonstrated that GWL and ODL were key drivers of hydraulic force requirements, with the model explaining up to 82.6% of the variability in ODL. Dual-force regulation enabled significant improvements in seedling emergence rate (up to 9.2%) and plant spacing uniformity (variability index as low as 0.12), particularly under moderate speed and downforce settings. Uplift and downforce pressures responded distinctly to changes in mechanical loads, with observed interactions between operational parameters and soil conditions. These findings confirm the technical and agronomic advantages of dual hydraulic force control over traditional downforce-only systems, supporting the adoption of adaptive, sensor-informed

regulation strategies to optimize crop establishment and stand uniformity under variable field conditions.

5.2 Introduction

Achieving uniform seed placement is critical for crop establishment and productivity, with downforce and gauge wheel load recognized as central components of planter performance. Downforce requirements vary substantially with soil texture, moisture, and terrain conditions (Poncet et al., 2018; Virk et al., 2021). Proper adjustment is essential, as seedlings' emergence uniformity and speed improve under adequate downforce (Oliveira et al., 2021; Poncet et al., 2019). Plant spacing uniformity, often measured by the coefficient of variation, likewise shows improvements with medium fixed and high active downforce levels (Badua et al., 2018; Virk et al., 2021). However, excessive downforce may reduce population and delay emergence, particularly under no-till conditions (Drewry et al., 2021; Poncet et al., 2019). Building on this agronomic understanding, numerous technological solutions have been developed to manage and optimize planter downforce. Comparative studies of mechanical, pneumatic, and hydraulic systems reveal notable performance differences across cropping environments. Spring-loaded mechanisms lack adaptability, often producing seed depth variations exceeding 21 mm between fields (Poncet et al., 2018). In contrast, pneumatic systems enable more accurate longitudinal placement and maintain stand uniformity at higher planter speeds (Cortez et al., 2020). Hydraulic and electro-hydraulic designs deliver the most substantial improvements, reducing seed depth variability while maintaining better gauge wheel contact, particularly under heavy soils that may require forces exceeding 1100 N (Oliveira et al., 2021; Virk et al., 2021). Thus, hydraulic approaches represent the most effective pathway to improving planting precision. Beyond the mechanical design and active hydraulic control systems, interactions between soil properties and planter forces further complicate planting dynamics. Apparent electrical conductivity (ECa) is widely recognized as a reliable indicator of soil variability, positively correlating with clay content and bulk density (Johnson et al., 2001; Mertens et al., 2008). In heavier soils with higher ECa, the force required for disk openers—known as opening disk load—increases significantly, influencing the planter's ability to penetrate and create the seed furrow (Badua & Sharda, 2023). Real-time monitoring systems have revealed that in approximately 10% of planting operations, excessive opening disk loads necessitate the use of uplift force to mitigate compaction risk and maintain optimal soil structure around the seed zone (Badua & Sharda, 2023). The management of gauge wheel load in these contexts is crucial: matching hydraulic downforce to local soil conditions ensures proper furrow closure and seed placement, while preventing detrimental compaction or inadequate seed coverage (Hanna et al., 2010). Experimental evidence shows that varying gauge wheel loads—typically categorized as light (180–490 N), medium (490–890 N), and heavy (>890 N)—differentially affect seed zone environment and early corn growth parameters, underscoring the need for adaptive force control strategies in variable soils (Hanna et al., 2010). The most significant advances in hydraulic systems have emerged from integrating electronic feedback and active control. These systems incorporate sensor-based feedback loops, often with PID (Proportional-Integral-Derivative) closed-loop algorithm regulation, to dynamically adjust row-unit loads and respond to rapid fluctuations in soil conditions (Jing et al., 2020; Li et al., 2020). Field and laboratory studies demonstrate that active hydraulic systems maintain target gauge wheel loads within ±223 N for 94% of operation time and adjust to variations up to 667 N within 1.3 seconds (Strasser et al., 2021). They consistently outperform fixed-force systems, improving seeding depth consistency by 1.05–2.23% and raising qualified seeding indices by 3.12–34.38% compared to conventional spring types (Jing et al., 2020).

Although sensitivity to ground speed remains a challenge—with slower travel generally favoring greater uniformity (Badua et al., 2018; Bai et al., 2020)—the benefits of active downforce control are well documented, and systems such as 'DeltaForce' are widely recognized for stabilizing planting depth across variable field conditions (Adee, 2021). Despite these achievements, a critical limitation of existing research is that nearly all active control systems exclusively focus on downforce. Most current designs apply hydraulic pressure downward on the planter units but neglect the potential advantages of simultaneously controlling upforce to adjust row-unit dynamics in the opposite direction. Recently, new electro-hydraulic technologies have emerged that integrate dual hydraulic circuits—one applying downforce and the other delivering uplift control—allowing real-time regulation of row unit position in both directions (Adee, 2021; Strasser et al., 2021). By lifting or lowering row units based on sensor input, these dual-force systems represent a promising step toward more precise planting regulation, especially under conditions with marked soil variability. However, such dual-force systems' agronomic and operational outcomes are little known. Published studies to date have primarily treated planter downforce as a unidirectional parameter, leaving a gap in understanding how uplift control and its interaction with downforce affect gauge wheel load stability and early crop establishment. Addressing this gap, this study aimed to evaluate the performance of a novel dual-hydraulic force control system for corn planters, designed to apply both downforce and uplift on the row units independently. Specifically, the research objectives are to: i) To investigate uplift control dynamics concerning planter speed and downforce margin variations; ii) To evaluate the response dynamics of a dual-force hydraulic system under varying gauge wheel load and opening disk load conditions, considering spatial soil variability, and to quantify the effects on hydraulic pressures and planter performance; and iii) Examine the implications for early seedlings’ emergence and in-row plant spacing.

By fulfilling these objectives, this study seeks to provide new insights into dual-force hydraulic systems' agronomic and operational potential, thereby addressing a critical gap in the existing planter downforce literature.

5.3 Materials and methods

5.3.1 Experiment design

The experiment was arranged in a split-plot design, with planter speed assigned to the main plots and downforce margin to the subplots. Two levels of planter speed (8.9 and 11.3 km h^{-1}) were evaluated, and within each planter speed, three levels of downforce margin (445, 778, and 1112 N) were applied, resulting in six treatment combinations. Each treatment was implemented in a single planter run, with the allocation of downforce margin levels randomized within each planter’s speed.

5.3.2 Site and crop description

The field trial was conducted in 2025 in Exeter Township, Clay County, in north-central Kansas, USA. The experimental site (39.2616928° N, 97.1537884° W) encompassed 54 hectares, with 3.08 hectares designated for experimental purposes. The soils at the site were classified as 100% Crete silty clay loam, characterized by slopes of 1 to 3 percent (Soil Survey Code 3828), according to USDA et al. (2025). Corn planting occurred on May 2, 2025, aiming for a target population density of 53,960 plants ha^{-1}. The corn hybrid utilized in this investigation was Golden Harvest® G08R552-V, which exhibited a germination rate of 95%. The experimental site was managed under a dryland, no-till agricultural system, following a corn-soybean rotation that commenced in spring 2020. Soil apparent electrical conductivity (ECa) was collected using an ECa DUALEM-1 sensor (Milton, ON, Canada) mounted on a John Deere utility vehicle (Moline, IL, USA). A soil ECa map was then generated using ArcGIS Pro (Redlands, CA, USA), delineating the field into different soil ECa zones.

5.3.3 Planter and row unit specification

All field operations were conducted using a John Deere 1775NT planter configured with 12 row units at 762 mm spacing, operated in conjunction with a John Deere 8R 410 tractor (Figure 5.1). The planter integrated the SeedStar™ 4HP system to monitor and manage planting performance. ISOBUS compatibility facilitated whole operation and monitoring through the in-cab display.

Figure 5.1. John Deere 1775NT 12row30 planter paired with a John Deere 8R 410 tractor used for all experimental field operations.

The planter row units utilized SurePoint (Atwood, KS) Ag Systems RFX™ suspension, which employs a patented hydraulic accumulator and a two-valve design to enable downforce and uplift control. Seed delivery on each unit was managed by SurePoint MVX™ electric drive seed meters, incorporating vacuum metering with stainless steel seed plates, a cast aluminum housing, and a brass singulator for reduced static electricity and simplified maintenance. For furrow closure, each row was fitted with SurePoint Curvetine® closing wheels (Figure 5.2).

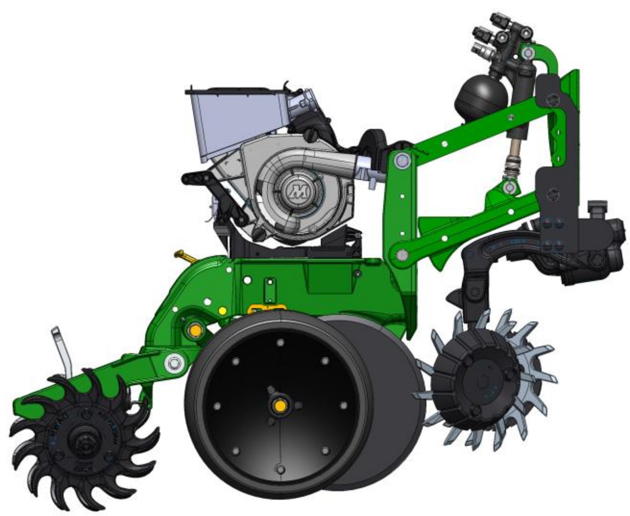

Figure 5.2. Detailed view of the John Deere 1775NT planter row unit, featuring SurePoint RFX™ hydraulic suspension, MVX™ vacuum seed meter, and Curvetine® closing wheel.

5.3.4 Data acquisition and sensor instrumentation

A custom data acquisition system was developed to monitor and record real-time planting parameters. Hydraulic pressure transducers model HAD 846K-A-5000-000 (HYDAC, Glendale Heights, IL) were installed on all planter row units to measure the hydraulic oil pressure applied to the downforce system. Additional transducers of the same type were positioned on rows 3 and 11 of the uplift hydraulic lines. These measurements directly quantified the active hydraulic downforce exerted by the planting system during operation, enabling the implementation and verification of target gauge wheel load values. With sub-inch accuracy, positional and velocity data were captured using a GR5 GPS receiver (Topcon Positioning Systems, Inc., Livermore, CA). Proprietary factory-installed load cells on the same row units measured GWL in real time throughout planting. All sensor outputs, including load cell, hydraulic pressure, and GPS signals, were acquired at a sampling frequency of 10 Hz via a custom LabVIEW (National Instruments, Austin, TX) interface, running on a Latitude 3400 laptop computer (Dell, Round Rock, TX) connected through a NI cRIO chassis outfitted with C Series modules (National Instruments, Austin, TX).

5.3.5 Post-planting data collection

5.3.5.1 Seedling labelling and emergence

After planting, 5.34 meters of experimental strips were established within each experimental unit, specifically along the furrows created by row units 3 and 11, counting the planter's row units from left to right. Observations regarding plant emergence and in-row plant spacing metrics were conducted within these designated areas. These experimental strips were monitored twice daily, at 8:00 AM and 6:00 PM, to track the onset and completion of plant emergence. Emergence was confirmed by checking for the coleoptile breaking through the soil in each strip. The initial time and date of emergence observed during the experiment were designated as the 'beginning of emergence.' This reference point served as a critical benchmark for subsequent analysis and interpretation of the results. The data generated from these measurements included the Emergence Rate Index (ERI). Any visible green shoots above the ground were marked using a wooden stake measuring 10 cm in length and 1 cm in width, labeled with a specific date and time code during the assessment. After full emergence, the plant identification numbers were recorded, corresponding to the sequence of plants from the start to the end of the strip. This was determined by noting the point at which the planter’s row unit began planting the strip and the last seed placed before the unit exited the strip based on its running direction. As introduced by Erbach (1982), and cited by Hanna et al. (2015), the ERI is a relative measure for evaluating the speed of corn emergence across various treatments. The ERI calculation aggregates multiple components, each representing the proportion of total plants that emerged on a specific day, divided by the number of days since planting, as illustrated in Equation 5.1. Higher ERI values indicate faster emergence rates across different treatments. It is important to note that the methodology used to assess seedling emergence has inherent limitations. The twice-daily visual inspections may miss seedlings emerging between observation times or those that emerge but die shortly afterward, potentially leading to underestimations of emergence rates. Manual marking of emerged seedlings assumes consistent and accurate identification without disturbing plants, though observer variability and field heterogeneity can affect reliability. Spatial sampling within experimental strips may not fully represent variability across the entire experimental field. Environmental factors such as microclimatic variability, soil moisture heterogeneity, and surface residue presence also influence emergence patterns independently of treatment effects. Despite these limitations, the approach provides a practical framework for comparative emergence analysis across treatments and environments.

5.3.5.2 In-row plant spacing assessment

During the V1 vegetative stage, as defined by Ciampitti et al. (2016), in-row plant spacing was evaluated using a 7.6-meter standard measuring tape (Stanley Black & Decker, New Britain, CT). The tape was aligned along experimental strips to record cumulative plant spacing. The theoretical plant spacing (TS) for each field trial was calculated based on seeding rate and row unit spacing, following the methodology of Badua et al. (2021). Plant spacing uniformity was quantified using indices derived from ISO 7256/1-1984(E) and detailed by Kachman & Smith (1995), as cited by Badua et al. (2021). These indices included the multiple index, miss index, quality of feed index (single plant index), precision index (here referred to as variability index), and coefficient of variation (CV). The multiple index represented the frequency of spacings ≤ 0.5×TS per strip, while the miss index indicated spacings > 1.5×TS. The quality of feed index measured the proportion of spacings within 0.5 to 1.5×TS, reflecting alignment with TS. The variability index captured spacing consistency by incorporating skips, doubles, and singles, with lower values implying more uniform spacing. Finally, CV served as a standard metric of spacing uniformity, with lower values denoting improved uniformity (Bisognin et al., 2019; Stewart et al., 2021). Some inherent limitations warrant consideration in assessing in-row plant spacing. The methodology assumes that seedling positions measured during the V1 stage accurately represent spatial distribution along the row, with minimal plant movement or mortality altering spacing. Manual tape measurements may be affected by operator variability, row curvature, and uneven field surfaces, potentially impacting precision. The spatial sampling along strips may not capture full field heterogeneity, and the indices used rely on accurate classification of skips, doubles, and singles, which can be ambiguous in closely spaced or irregular stands. Additionally, the calculation of theoretical spacing assumes uniform planter operation and consistent seeding rates; any deviations can propagate into spacing uniformity metrics. Despite these limitations, the approach offers standardized, practical measures for comparing treatment effects on spatial uniformity in corn stands.

5.3.6 Statistical analysis

Field-collected post-planting sampling data from experimental strips were organized and initially processed using Microsoft Excel 365 (Microsoft Corporation, Redmond, WA). A factorial analysis of variance (ANOVA) was conducted to assess the effects of planter speed, CWD, and their interaction on the measured response variables. Tukey’s post-hoc test for multiple comparisons with type I error correction was applied to identify statistically significant differences among treatment combinations. The base R Studio version 2023.06.1+ (Posit PBC, Boston, MA) function TukeyHSD and the ‘agricolae’ package were utilized to perform these analyses and generate grouping letters for visual interpretation of treatment differences. For data visualization, the matplotlib (version 3.7.1) and seaborn (version 0.13.2) libraries were used to generate clear and informative graphics in Python.

5.4 Results and discussion

5.4.1 Hydraulic pressure dynamics

Consistent with prior reports highlighting the critical role of controlled downforce and gauge wheel load in securing uniform seed placement (Poncet et al., 2018; Virk et al., 2021), the present results demonstrate that operational setpoints and planter speed strongly influence both uplift and downforce hydraulic pressures in the tested dual-force system. The regression analysis for uplift hydraulic pressure revealed a significant positive effect of planter speed, with uplift pressure rising by approximately 65.74 kPa for every 1 km h^{-1} increase. This finding aligns with the documented responsiveness of active hydraulic systems to varying field speeds (Jing et al., 2020; Strasser et al., 2021), particularly under rapidly changing soil conditions. Furthermore, the significant, positive interaction coefficient detected indicates that the sensitivity of the uplift circuit to speed is enhanced at higher downforce margin settings, underscoring the dynamic nature of dual-force control when both uplift and downforce setpoints vary simultaneously (Figure 5.3). Conversely, uplift hydraulic pressure decreased by 7.39 kPa for each unit increase in downforce margin, provided speed remains constant. This highlights the balancing interplay between downward and upward hydraulic circuits in modulating planter row-unit forces—a mechanistic dimension absent in most previous studies, which have focused almost exclusively on downforce (Adee, 2021; Strasser et al., 2021). Notably, dual-force regulation produced results that are theoretically consistent with the precision improvements reported for single-direction active control systems, while also revealing new interdependencies that may further stabilize gauge wheel load and corn seed placement, especially in fields with variable soil firmness.

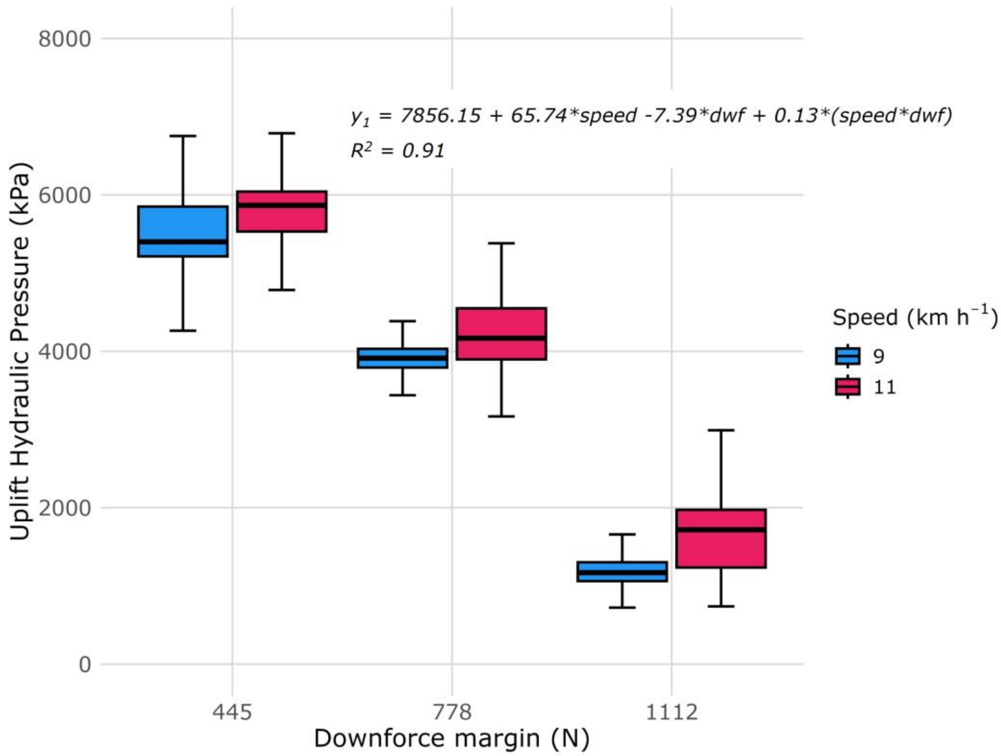

Figure 5.3. Boxplots depict recorded uplift hydraulic pressure across planter speed and downforce margin treatments, illustrating their main effects and interaction. The response variable uplift hydraulic pressure (y1) was analyzed via multiple linear regression, including planter speed (speed) and downforce margin (dwf) as covariates.

The regression analysis for downforce hydraulic pressure extends these insights. Here, planter speed and downforce margin exerted significant positive effects, increasing hydraulic pressure by 221.91 kPa and 5.29 kPa, respectively, per unit change. However, the negative interaction coefficient observed (−0.22) demonstrates that as downforce margin rises, the impact of speed on hydraulic pressure is attenuated. This buffering effect suggests higher downforce margin settings and dynamic control prevent overreactive pressure changes under fast operational conditions. This finding complements earlier observations by Badua et al. (2018) and Bai et al. (2020), regarding the need for stability at elevated travel speeds (Figure 5.4).

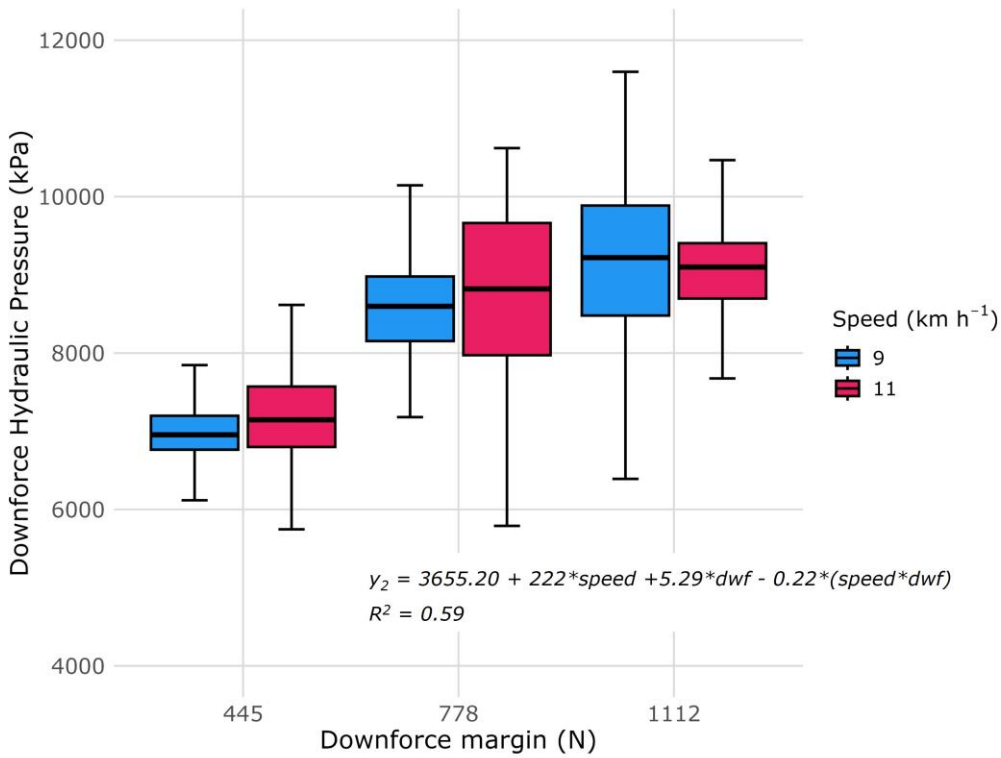

Figure 5.4. Boxplots depict recorded downforce hydraulic pressure across planter speed and downforce margin treatments, illustrating their main effects and interaction. The response variable downforce hydraulic pressure (y2) was analyzed via multiple linear regression, including planter speed (speed) and downforce margin (dwf) as covariates.

This analysis expands on previous studies that concentrated solely on downforce by exploring the relationship between downforce and uplift load in conjunction with other factors influenced by soil and field conditions. These factors include soil resistance to furrow opening, represented here by the ODL, as well as the resulting GWL recorded on the gauge wheels of the row unit evaluated. The experimental area displayed substantial spatial variability in soil properties and mechanical load response, as depicted in Figure 5.5. The ECa map revealed heterogeneous soil conditions, which correlated strongly with the distribution of ODL measurements along the planter runs. A significant correlation was observed between the values obtained from the ODL (y_3 in the model) and the measured values of ECa in the field and the GWL in the row units, with a coefficient of determination (R^2) of 82.56%. This high explained variance confirms soil spatial properties as primary drivers of mechanical forcing at the soil-tool interface, supporting prior observations by Poncet et al. (2018) and Virk et al. (2021) on the influence of soil conditions on planter downforce requirements. The spatial correspondence between ECa patterns and ODL reinforces the need for adaptive hydraulic control systems capable of dynamically responding to such field-scale variability.

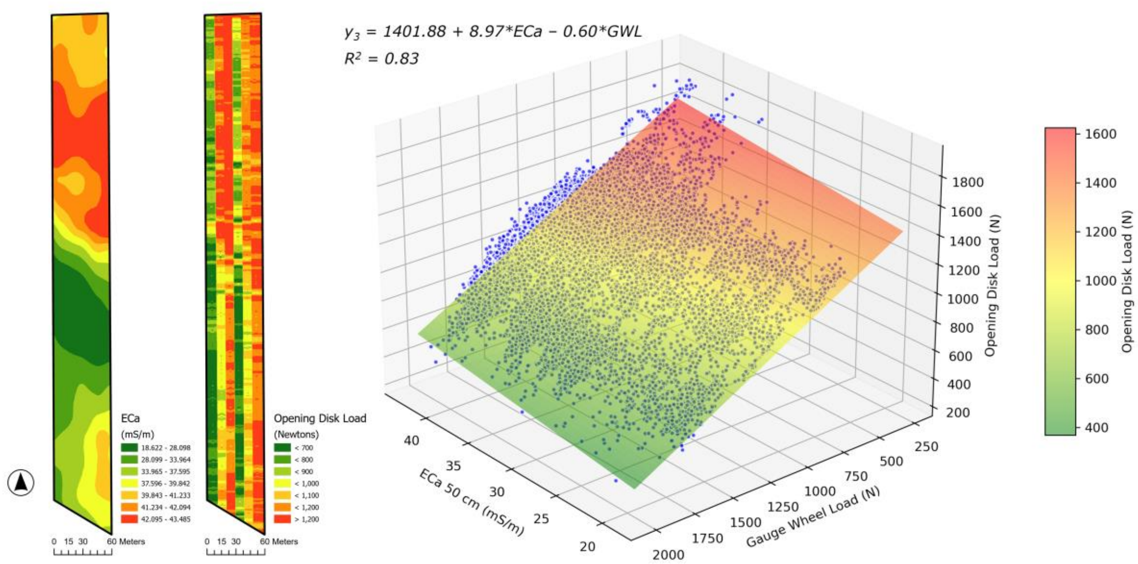

Figure 5.5. Spatial maps of soil electrical conductivity (ECa) and opening disk load (ODL) in the field. Left: ECa zones by texture and moisture. Right: ODL variability during planting. 3D plot shows ECa, gauge wheel load (GWL), and ODL; linear model (R^2 = 0.83) quantifies ODL from ECa and GWL.

Building on this foundational context, Figures 5.6 and 5.7 present the hydraulic responses of the dual-force systems—uplift and downforce pressures—relative to the mechanical loads of gauge wheels and opening disks, respectively. Hydraulic pressures exhibited contrasting but complementary behaviors concerning GWL (Figure 5.6). Uplift pressure decreased by approximately 4.57 kPa per Newton increase in GWL, while downforce pressure increased by 2.46 kPa per Newton increment. The respective model fits (R^2=0.79 for uplift and 0.57 for downforce) affirm that gauge wheel load is a dominant factor modulating hydraulic responses, consistent with earlier findings connecting gauge wheel management to seed placement uniformity and emergence speed (Badua et al., 2018; Oliveira et al., 2021). The opposing trends reflect the physical mechanics of the dual-force system, where downforce application naturally counters uplift forces to maintain consistent seedbed penetration, a crucial aspect underscored in reviews by Drewry et al. (2021) and Poncet et al. (2019). A closer examination of Figure 5.6 reveals three distinct clusters in the distribution of points related to both downforce and uplift hydraulic pressure, corresponding to the three applied downforce margin treatments of 445, 778, and 1112 N. The figure clearly illustrates how the dual system seeks to balance the load on the planting bodies by increasing the upward load when the body operates with a lighter margin, such as at 445 N, and by decreasing it when the downward load demands are greater, as seen with the 1112 N margin.

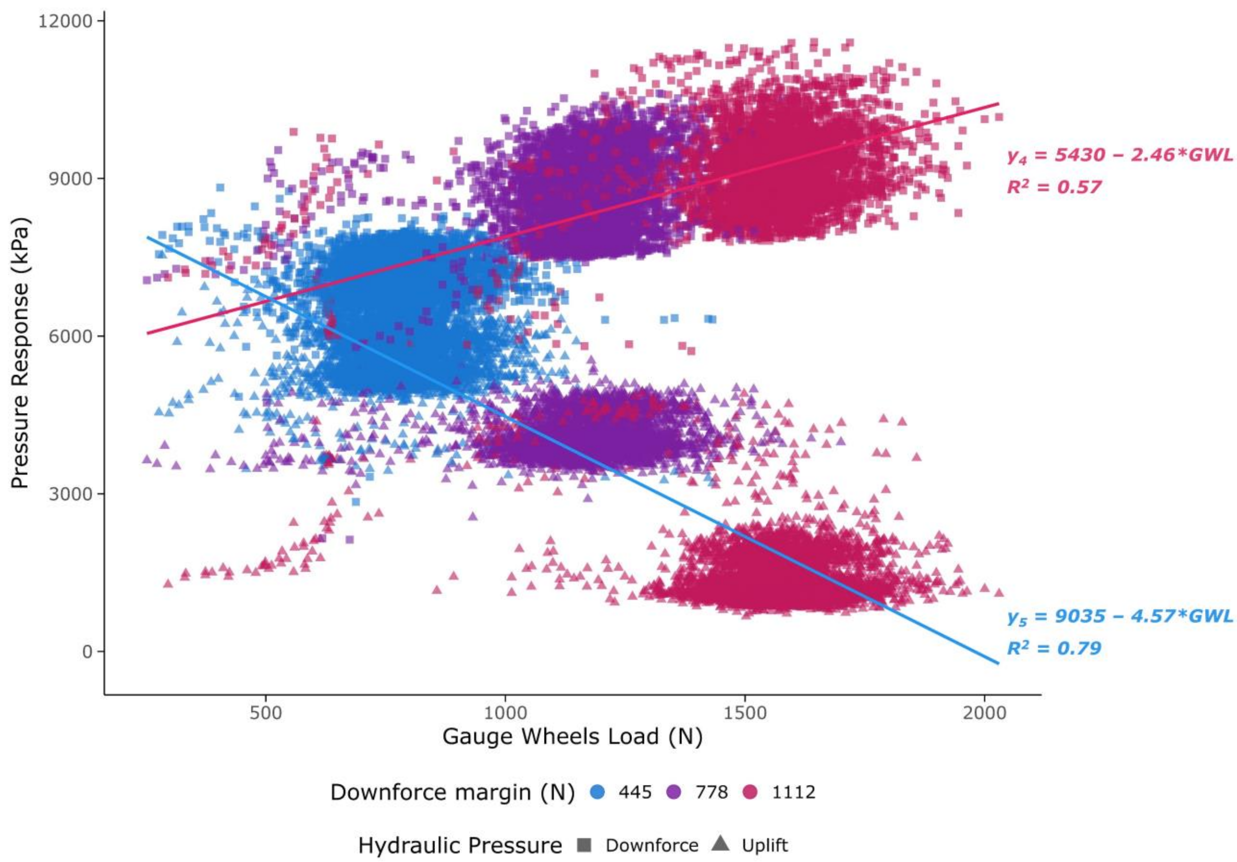

Figure 5.6. Relationship between gauge wheel load and hydraulic pressure responses in a dual-force hydraulic system. Scatter points represent uplift (triangles) and downforce (squares) hydraulic pressures across three downforce margin treatments (445, 778, and 1112 N). Fitted linear models demonstrate inverse hydraulic behaviors: uplift pressure decreases while downforce pressure increases with higher gauge wheel load (GWL). The linear relationships indicate predictable circuit sensitivity, with uplift pressure ranging from ~2000-6000 kPa and downforce pressure ranging from ~6000-10000 kPa across the experimental GWL range. Regression coefficients and R^2 values quantify the strength and direction of each pressure response to mechanical loading conditions.

When analyzed against opening disk load (Figure 5.7), hydraulic pressures demonstrated varied sensitivities. Uplift pressure showed a relatively strong positive association with ODL, increasing by about 5.81 kPa per Newton increase (R^2=0.62), indicative of an effective linkage between upward hydraulic actuation and soil resistance measured at the disk. Conversely, downforce pressure weakly decreased by 1.64 kPa with each newton of ODL increase (R^2=0.12), suggesting that downward hydraulic response may rely on additional factors beyond simple loading at the opener, or that the dual system's downforce circuit is less responsive to this metric under the study conditions. This aligns with the nuanced mechanisms proposed by Strasser et al. (2021), for active hydraulic systems, which emphasize the importance of multi-parameter feedback and the potential for hydraulic decoupling in complex field environments.

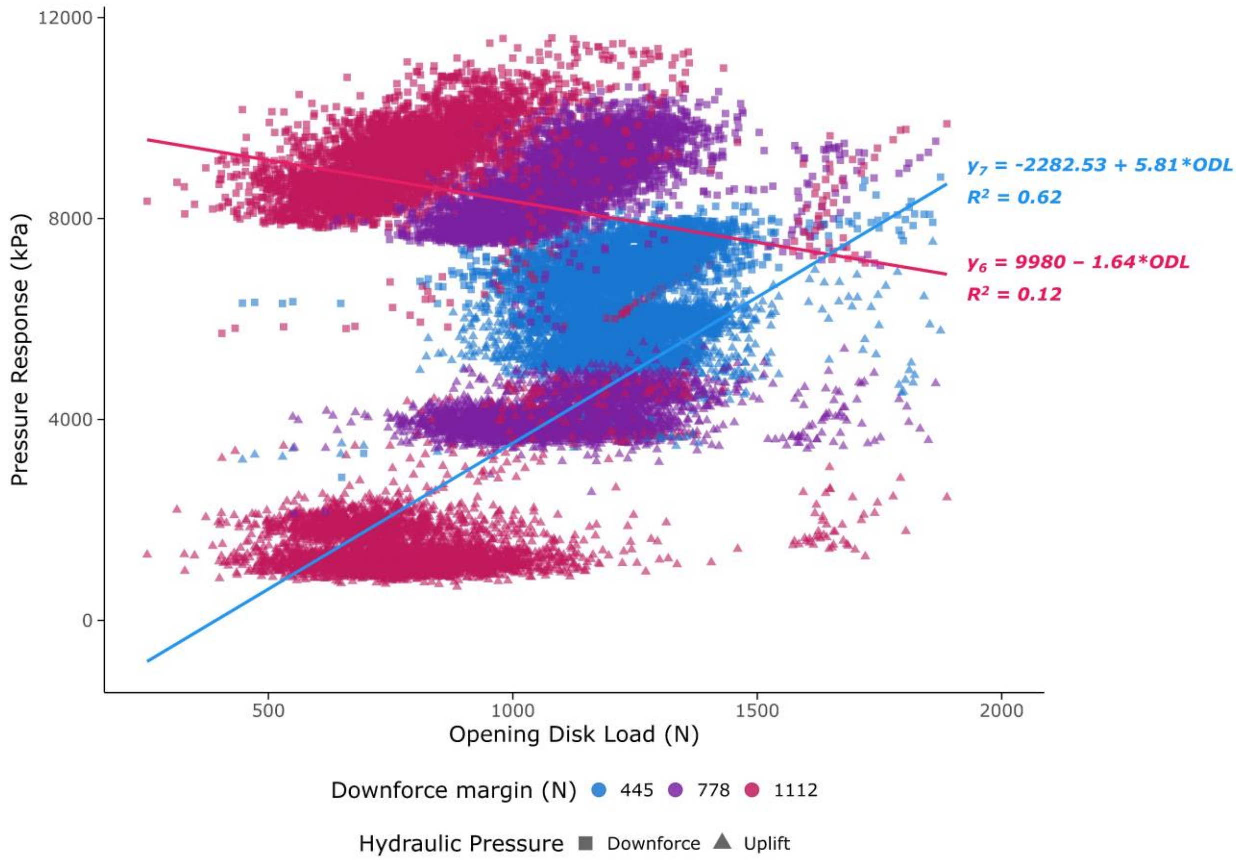

Figure 5.7. Relationship between opening disk load and hydraulic pressure responses in a dual hydraulic system. Scatter points represent uplift (triangles) and downforce (squares) hydraulic pressures across three downforce margin treatments (445, 778, and 1112 N). Fitted linear models demonstrate contrasting hydraulic behaviors: uplift pressure increases while downforce pressure decreases with higher opening disk load (OPD). The linear relationships indicate predictable circuit sensitivity, with uplift pressure ranging from ~2000-6000 kPa and downforce pressure ranging from ~6000-10000 kPa across the experimental OPD range. Regression coefficients and R^2 values quantify the strength and direction of each pressure response to disk loading conditions.

Collectively, these results substantiate the efficacy of dual-force hydraulic control systems in dynamically modulating row-unit forces in response to both terrain heterogeneity and varying machine operational parameters. By integrating spatial soil characteristics with mechanical force measurements and hydraulic responses, this work advances the understanding of precision planter performance, echoing agronomic recommendations for optimizing seed placement through adaptive downforce and uplift regulation (Adee, 2021; Jing et al., 2020). The observed interaction effects and differential sensitivities underscore the value of holistic hydraulic system designs that can simultaneously adjust multiple force vectors to achieve uniform seed emergence and consistent plant stands in challenging soil conditions.

5.4.2 Post-planting response to hydraulic regulation

Building upon the hydromechanical responses discussed above, post-emergence evaluation revealed clear impacts of planter speed and downforce margin on seedling emergence and plant spacing uniformity. The results presented in Table 5.1 summarize the ERI, multiple index, miss index, and quality of feed index for each treatment combination. Notably, ERI and quality of feed index were generally highest at moderate downforce margins (1112 N at 9 km h^{-1} and 778 N at 11 km h^{-1}), while both miss index and multiple index values tended to increase under extreme combinations of either high speed or insufficient downforce. These trends align with prior findings that optimal force settings and moderate operational speeds promote superior stand establishment by minimizing skips and doubles (Poncet et al., 2018; Virk et al., 2021).

Table 5.1. Mean values of emergence rate index (ERI), miss, double, and quality of feed indices by planter speed and downforce margin. Lowercase letters within each index indicate significant differences ($p<0.05$).

Planter speed (km h^{-1})	Downforce margin (N)	ERI	Multiple index (%)	Miss index (%)	Quality of feed index (%)
9	445	9.19 a	2.32 a	6.97 b	90.70 b
	778	9.03 b	0.00 b	12.50 a	87.50 c
	1112	9.20 a	2.38 a	4.76 b	92.85 a
11	445	8.91 b	0.00 b	15.78 a	84.21 c
	778	9.18 a	0.00 b	7.50 b	92.50 a
	1112	8.56 c	0.00 b	12.82 a	87.17 c

Figure 5.8 further illustrates that the variability index and the coefficient of variation (CV) of plant spacing were both lowest under combinations of moderate speed and downforce, particularly at 9 km h^{-1} and 1112 N, mirroring treatments with higher ERI and quality of feed scores. These observations reinforce established literature highlighting the agronomic importance of maintaining stable row-unit forces to optimize both emergence and spatial uniformity (Jing et al., 2020; Oliveira et al., 2021), and demonstrate the practical benefits of dual hydraulic force regulation observed earlier in this experiment.

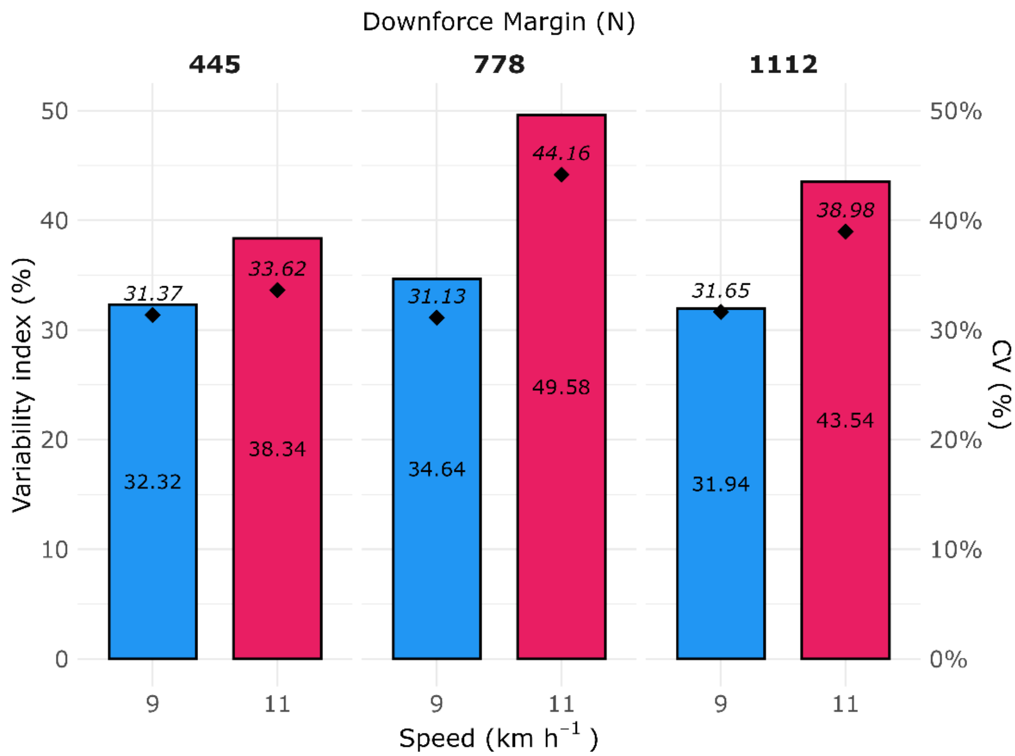

Figure 5.8. Variability index (bars) and coefficient of variation (CV, diamonds) of plant spacing by planter speed and downforce margin. Lower values indicate greater in-row uniformity.

Overall, these final results establish a clear linkage between real-time hydromechanical control during planting and measurable improvements in early-stage establishment. The ability of the dual-force prototype to actively regulate both uplift and downforce—with positive impacts on emergence rate, reduction of seeding errors, and improved spatial precision—directly supports the conceptual framework advanced in earlier studies. These results corroborate recommendations to employ adaptive, sensor-informed force control strategies to maximize crop performance under variable field conditions (Adee, 2021; Strasser et al., 2021), and close the section by affirming the agronomic and engineering promise of dual hydraulic regulation for precision planting systems.

5.4.3 Discussion of uncertainty and methodological limitations

The findings on the effects of planter speed and downforce margin on seedling emergence and plant spacing uniformity provide valuable insights into precision planting performance. However, several methodological limitations and sources of uncertainty should be acknowledged. The ERI and spacing indices depend on accurate and consistent identification and measurement of seedlings within experimental strips, which can be affected by observer variability and field heterogeneity. Manual estimation of indexes such as misses, multiple, and quality of feed assumes precise classification of skips, doubles, and singles, but borderline cases or ambiguous positioning can lead to classification errors. Operational variability in implementing dual hydraulic force regulation, along with environmental factors such as soil texture and moisture variability, also contributes to measurement inconsistency. Furthermore, planter speed and downforce generate complex interactive effects that may not be fully isolated in this study's design. These limitations add uncertainty to the magnitude of treatment effects on early stand establishment metrics. The consistent observation of improved emergence and spacing uniformity at moderate downforce and speed levels aligns with agronomic expectations but should be interpreted within these constraints.

5.5 Conclusions

This study demonstrates that dual-force hydraulic regulation in precision planters enables real-time, adaptive control of uplift and downforce pressures in response to spatial and operational variability. The integration of spatial soil properties, mechanical load measurements, and hydraulic responses revealed that both gauge wheel load and opening disk load are key drivers of hydraulic force requirements, with significant implications for seedbed engagement and row-unit stability. The dual-force system's ability to modulate hydraulic pressures according to changing field conditions resulted in measurable improvements in seedling emergence rate, reduction of seeding errors, and enhanced spatial uniformity of plant stands.

The observed interactions between planter speed, downforce margin, and soil mechanical properties highlight the importance of multi-parameter, sensor-informed control strategies for optimizing planting performance. These findings confirm and extend previous research advocating for active, adaptive force regulation in precision agriculture (Adee, 2021; Jing et al., 2020; Strasser et al., 2021). By providing quantitative evidence of the agronomic and engineering benefits of dual hydraulic regulation, this work supports the continued development and adoption of advanced force control systems to maximize crop establishment and yield potential under variable field conditions.

Future research should expand upon the foundations established in this study by conducting trials of dual-force hydraulic across various seasons and locations. It should also examine additional factors related to row unit behavior, such as acceleration and tilting, while incorporating new post-planting metrics like seed depth and yield per plant. Furthermore, research should investigate the integration of advanced sensing and control algorithms to enhance the robustness and adaptability of dual-force hydraulic systems in commercial agriculture. To address the spatial complexity and heterogeneity observed in hydraulic, mechanical, and stand establishment data, future research should implement advanced spatial statistical approaches. Geostatistical techniques such as variogram analysis, ordinary and regression kriging could be used to quantify and predict spatial autocorrelation in gauge wheel load, opening disk load, and emergence outcomes. Spatial regression models—including spatial lag and error models—would allow for more rigorous assessment of localized dependencies and interactions in planter performance metrics. Furthermore, Bayesian spatial hierarchical models and Bayesian kriging offer a powerful means to model spatial uncertainty and incorporate multiple data sources or process-level knowledge, yielding probabilistic maps of both performance and uncertainty. This integration of spatial and Bayesian methods would enable the identification of distinct management zones, facilitate uncertainty quantification for decision support, and support more robust, adaptive site-specific adjustment of hydraulic control strategies in precision planting.

Chapter 6 - Summary of contributions and future research agenda

6.1 General conclusions

This doctoral research provides a comprehensive evaluation of the multifactorial effects of planter operational parameters, component design, and soil variability on corn stand establishment and early crop performance under precision agriculture systems through the following findings:

a. The interaction between hydraulic downforce magnitude and planting speed significantly influences seed depth uniformity, early emergence rate, and plant spacing consistency. Lighter downforce combined with moderate speeds accelerated seedling emergence, but heavier downforce at lower speeds promoted deeper, more consistent seed placement. However, the effect of downforce was diluted at higher speeds, emphasizing the need for speed-specific force adjustments. Additionally, spatial variability among row units within a planter toolbar necessitates differentiated downforce management rather than uniform settings for optimal seed placement.

b. Secondly, planter speed and closing wheel design are critical determinants of seedling emergence uniformity and probability, further strongly modulated by soil temperature and moisture. While faster speeds generally reduce emergence likelihood and increase stand variability, particular closing wheel designs can mitigate these effects, highlighting the importance of matching closing wheel design selection to site-specific environmental conditions to maximize plant establishment and yield potential.

c. Thirdly, the choice and calibration of closing wheel systems in conjunction with planting speed decisively affect seed placement accuracy, spatial uniformity of plants, and final stand population. Specific aftermarket closing wheels demonstrated the capacity to maintain precision at elevated speeds and under challenging soil conditions, thus enhancing crop establishment. These results underscore the need for integrated equipment and operational calibration tailored to specific field scenarios.

d. Finally, the implementation of dual hydraulic force regulation systems, capable of simultaneously modulating downforce and uplift, shows substantial promise in dynamically adapting row unit soil engagement to spatial and operational variability. This adaptive control improves seedbed conditions, significantly enhances seedling emergence rates, reduces spacing errors, and fosters more uniform plant population distribution. These findings provide novel empirical support for advancing precision planter technology towards intelligent, sensor-based multi-parameter control strategies to optimize crop establishment under real-world variable conditions.

Collectively, this work advances understanding of the complex interactions among planter mechanics, operation, and environmental factors crucial for optimizing corn stand establishment in precision agriculture, offering valuable insights for the development of robust, adaptive planting technologies and agronomic guidelines to maximize productivity and sustainability in modern row crop systems.

6.2 Practical implications for stakeholders in the U.S. Midwest

The findings of this doctoral research offer several actionable insights relevant to planting equipment manufacturers and rural extension agents working within Midwestern corn production systems:

a. For Equipment Manufacturers: The demonstrated importance of dynamically adjusting hydraulic downforce and uplift according to planter speed and soil variability underscores the need to advance dual-force hydraulic control systems. Equipment designs should prioritize real-time sensor feedback integration and modular adaptability for individual row units, enabling precise force modulation that optimizes seed depth uniformity and seed-to-soil contact in heterogeneous field conditions. Furthermore, closing wheel system innovations—such as spiked or variable geometry wheels—should be further developed and tested at commercial scale to maintain seed placement performance even at increased planting speeds typical of modern operations.

b. For Rural Extension Agents: Effective dissemination of knowledge regarding the interactions among downforce settings, planting speed, and furrow closing device choice is essential to enhance grower decision-making. Tailored recommendations emphasizing site-specific adjustment of planter parameters, informed by soil texture, moisture, and residue cover variability, will improve stand establishment and yield stability. Additionally, promoting understanding of the limitations of fixed-force systems and encouraging adoption of emerging adaptive hydraulic technologies can foster greater planter performance and economic returns.

6.3 Future research directions

Building on the findings of this doctoral research, future work should explore integrating advanced multi-sensor arrays and machine learning algorithms to enable autonomous, real-time control of planter hydraulic forces. Large-scale multi-season field trials across diverse soil types and cropping systems are necessary to rigorously quantify the agronomic and economic benefits of dual-force hydraulic regulation under realistic operational conditions. The application of spatial statistical methods—including geostatistical techniques such as variogram analysis and kriging, spatial regression models, and Bayesian hierarchical approaches—should be prioritized to capture and model the complex spatial structure and uncertainty inherent in mechanical, hydraulic, and emergence data collected at the field scale. Such analyses will enable improved mapping of system performance, identification of management zones, and design of site-specific hydraulic control strategies. Investigating the interaction between precision planting and variable-rate input technologies to optimize fertilizer and pesticide application could further improve resource-use efficiency and yield stability. Moreover, the development of mechanistic models simulating soil-planting machine dynamics would enhance predictive understanding of seed placement outcomes influenced by complex soil-machine interactions. Lastly, comprehensive economic and environmental impact assessments of emerging planter technologies can guide sustainable adoption by producers and stakeholders in Midwestern agricultural systems.

6.4 Final reflection

Collectively, this thesis advances precision planting science by integrating multifactor operational, mechanical, and environmental analyses to optimize corn stand establishment. The insights gained provide both empirical evidence and practical guidance that hold promise for enhancing planter design and management strategies, promoting more consistent and efficient crop production in spatially variable field environments. It is anticipated that the continued development and deployment of adaptive planting technologies underpinned by rigorous research will play a vital role in meeting the productivity and sustainability challenges facing modern agriculture.

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