

Data-driven approaches to improve seed depth consistency in precision planting system

by

Simran Dua

B.Tech., Punjab Agricultural University, 2022

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

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

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2025

Approved by:

Major Professor
Dr. Ajay Sharda

Copyright

© Simran Dua 2025.

Abstract

Planting is one of the most crucial operations in crop production, as it determines how well a crop establishes and performs throughout the season. The goal of planting is to place each seed at an appropriate spacing and depth in the soil in a timely manner. While spacing ensures desired plant stand, accurate seeding depth ensures proper seed-to-soil contact, placement in adequate moisture zone, and favorable temperature conditions for uniform germination for all seeds. Consistent seeding depth plays a critical role in early-stage crop performance such as emergence rate and plant density, key factors influencing final yield. Despite major advances in precision planting technology, good is still a major challenge, especially when moisture plays a critical role in initial plant establishment. However, there is a need for technology which can not only place the seed in the right moisture zone by real-time changing seeding depth but can also provide uniform emergence to achieve optimal yields.

This research was designed to address key questions in precision planting, 1) How margin selection and operating speed impact GWL and seed depth uniformity 2) Can a variable depth seeding system provide accurate seeding depth at varying target depths under variable field conditions and, 3) Can a variable-depth seeding system promote uniform emergence for achieving optimal yields.

To answer these, two complementary studies were conducted focusing on planter mechanics and agronomic outcomes. The first study, Optimization of Gauge Wheel Load (GWL) Margin to Improve Planter Performance, evaluated the effects of four downforce margins (445 N, 778 N, 1112 N, 1446 N) and three planting speeds (8, 12, 16 km h⁻¹) on seeding depth consistency. This study was conducted to see if the planter can manage uniform downforce management, one key factor when

implementing seeding. Field data on seed depth, GWL, speed, and row-unit acceleration were analyzed using linear regression and visualization methods. Results showed that the control system implemented target GWL, and within GWL margins around 1112 N produced the most consistent seed depth (30% lower variability). Higher and more stable GWL margins improved soil contact, reduced compaction, and enhanced planter stability across varying field conditions.

The second study, Quantifying Emergence Uniformity Using an Electronic Depth (E-Depth) Control System, examined how planting depth affected emergence timing and yield across different fields. Three target depths (1.5, 2.0, and 2.5 in) were implemented using a precision planter equipped with real-time electronic depth control. Data on emergence, actual depth, and yield were analyzed using logistic regression and ANOVA. The 2.0-inch depth consistently resulted in faster, more uniform emergence and more stable yields under diverse field environments, while the deeper 2.5-inch depth resulted in delayed emergence that required on average approximately 5 additional days to reach 95% emergence.

These studies provide a comprehensive understanding of how optimizing both mechanical (GWL margin) and agronomic parameters can achieve precise and consistent seeding depth. The findings deliver data-driven insights to improve planter performance, enhance stand establishment, and support smarter, digital-agriculture decisions for producers.

Table of Contents

List of Figures	vii
List of Tables	viii
Acknowledgements	ix
Dedication	x
Chapter 1 - Introduction.....	1
Chapter 2 - Optimization of GWL margin to enhance planter performance	3
ABSTRACT	3
INTRODUCTION.	4
Materials and Methods.....	7
Study area and crop description	7
Row crop planter	8
Experimental Design.....	9
Seeding Depth	10
Data analysis	10
Results and Discussion	12
Depth accuracy using Mean deviation of depth from target depth	12
Variance Modeling for Depth	13
GWL CV and depth consistency.....	14
Influence of different variables on GWL	15
Ride quality and its relationship with GWL margin	17
Speed of planter interaction with GWL Margin	18
Sectional GWL variation across planting speeds.....	20
Conclusions.....	21
Chapter 3 - Quantifying emergence uniformity using E-Depth in seeding system	23
Introduction.....	23
Material and Methods	27
Site Description.....	27
Planting Equipment.....	28
Experimental design.....	29

Post Planting measurements	29
Emergence.....	29
Seeding depth.....	30
Data analysis	31
Result and Discussion.....	32
Achieved seed depth relative to target depth	32
Live Plant Population.....	33
Emergence dynamics with planting depth	34
Emergence Uniformity with Time (DAE)	34
Emergence Uniformity with Covariates	39
Field A (Kopfers).....	39
Field B (TownsEnd).....	40
Field C (Griffiths)	40
Field D (R&R)	41
Emergence with GDD.....	42
1.5-Inch Planting Depth.....	42
2.0-Inch Planting Depth.....	43
2.5-Inch Planting Depth.....	43
Yield.....	44
Yield response to planting depth.....	44
Yield response to interaction of planting depth and Emergence	45
Conclusion	48
Chapter 4 - Conclusion	50
References.....	52

List of Figures

Figure 2.1 Precision planter	9
Figure 2.2. GWL v/s Downforce	15
Figure 2.3. CV GWL v/s Downforce.....	15
Figure 2.4. Seed Depth v/s Downforce.....	15
Figure 2.5. GWL v/s Seed depth on varying speed	16
Figure 2.6 Sectional graphs for 8 km/h.....	21
Figure 2.7 Sectional graphs for 12 km/h.....	21
Figure 2.8. Sectional graphs for 16 km/h.....	21
Figure 3.1. Precision planter	29
Figure 3.2. Emergence measurements	30
Figure 3.3. Depth measurement	31
Figure 3.4. Field A Mean Seed Depth	33
Figure 3.5. Field B Mean Seed Depth.....	33
Figure 3.6. Field C Mean Seed Depth.....	33
Figure 3.7. Field D Mean seed Depth.....	33
Figure 3.8. Overall emergence curve.....	35
Figure 3.9. Field A Emergence curve	38
Figure 3.10. Field B Emergence curve	38
Figure 3.11. Field C Emergence curve	38
Figure 3.12. Field C Emergence curve	38
Figure 3.13. Surface graph for emergence with soil temperature and DAE.....	42
Figure 3.14. Yield response to emergence and depth- Griffiths	46
Figure 3.15. Yield response to emergence and depth- R&R	46

List of Tables

Table 3.1. Live plant population and population loss.....	34
Table 3.2. Time to event emergence indices.....	38
Table 3.3. Emergence and GDD	43
Table 3.4. ANOVA for emergence and depth interaction	47

Acknowledgements

I would like to express my deepest gratitude to my major advisor, Dr. Ajay Sharda, for his continuous support, guidance, and encouragement throughout my research journey. His valuable insights, constructive feedback, and unwavering mentorship have been instrumental in shaping this work and bringing it to completion.

I extend my sincere appreciation to my committee members, Dr. Trevor Hefley and Dr. Ignacio Ciampitti, valuable suggestions and insightful perspectives that strengthened both the scientific and analytical dimensions of my research.

My heartfelt thanks go to all my colleagues, FARMS Lab team, for their support during my time at Kansas State University. Special thanks to both current and former members of the Precision Planting team Bhaskar Aryal, Jose Peiretti, Bautista Gigena Berretta, Mark Daniel Estrada, Francisco Selva, Aashvi Dua and Rahul Singh for their constant help, cooperation, and dedication in conducting field experiments and data collection.

Finally, I express my deepest appreciation to my parents for their unconditional love and encouragement that has been my constant source of strength. Last but not least, I would like to thank my sister, Aashvi Dua, for her unwavering support, patience, motivation, and affection, which inspired me throughout this journey. Their belief in me has made the completion of this thesis possible.

Dedication

To the one who envisioned this journey for me long before I did, with heartfelt love, deep respect, and sincere gratitude.

Chapter 1 - Introduction

Planting is one of the most crucial operations in crop production, as it determines how well a crop establishes and performs throughout the growing season. Over the past few decades, planting methods have evolved from manual broadcasting of seeds to the use of sophisticated agricultural machinery, revolutionizing crop establishment. The mechanization era marked a significant turning point in agricultural productivity by improving seed placement accuracy, resulting in better plant stands and higher yield potential compared to traditional broadcasting methods. Building upon this progress, recent decades have witnessed the rise of precision planting systems, which represent the next leap in seeding technology.

Precision planting integrates electromechanical sensors, variable-rate controllers, and real-time feedback mechanisms that continuously monitor soil conditions, machine dynamics, and seed placement quality. These systems allow planters to automatically adjust seeding depth, downforce, and population in real time to achieve optimal seed placement under variable field conditions (Virk et al., 2020). Despite these advances, challenges remain in translating technological capability into consistent agronomic performance. Farmers still struggle to maintain accurate seeding depth and uniform emergence when soil moisture and structural conditions vary across the field, which ultimately limits yield potential and input-use efficiency.

This disconnect highlights a broader issue in precision agriculture while technology has advanced rapidly, decision-making on how to integrate machine feedback with agronomic variability remains a key bottleneck. The next era, digital agriculture, must therefore emphasize data-driven decisions that interpret planter sensor data, optimize operational parameters, and provide actionable insights for field-specific management. The integration of data science and analytics into precision planting is essential for achieving adaptive and predictive planting systems.

Among all planter settings, seeding depth remains one of the most sensitive and critical adjustments. Accurate depth ensures adequate seed-to-soil contact, proper placement within the moisture zone, and favorable temperature conditions for uniform germination and seedling emergence (Virk et al., 2020). Inconsistent seeding depth can lead to uneven soil contact and variable moisture exposure, resulting in delayed or uneven emergence, poor stand establishment, and reduced yield potential. Every seed's success begins below the surface where depth decides its fate. Given the critical role of depth, the producers face these key questions in precision

planting, 1) How does margin selection and operating speed impact GWL and seed depth uniformity? 2) Can a variable depth seeding system provide accurate seeding depth at varying target depths under variable field conditions and, 3) assess if variable depth can provide uniform rate emergence for optimal yields.

Even with advanced planting systems, achieving uniform emergence remains challenging in the presence of natural soil variability. Thus, optimizing both mechanical parameters (that control how the planter interacts with soil) and agronomic parameters (that govern plant response) becomes essential. This research was designed to address these gaps by integrating planter performance dynamics with agronomic outcomes. It is structured around two complementary studies:

1. Optimizing gauge wheel load margin (GWL) margin to enhance planter performance, and
2. Quantifying emergence uniformity using the electronic-depth (E-Depth) control system in precision seeding

Together, these studies will provide a comprehensive, data-driven understanding of how to define, achieve, and maintain accurate seeding depth in real-world conditions. By linking mechanical optimization with agronomic performance, this research will contribute to improving planter control strategies, enhancing emergence uniformity, and supporting digital agriculture approaches that help farmers make informed and efficient seeding decisions.

Chapter 2 - Optimization of GWL margin to enhance planter performance

ABSTRACT

Planter performance is usually evaluated using its ability to plant seed at desired seed rate and uniform planting depth. Uniform seeding depth is a major factor in plant emergence which ultimately affects the yield of the crop. The downforce control system of the precision planters maintains the uniform planting depth by adapting to varying soil characteristics in the field. Downforce is the amount of pressure exerted by row unit of planter on the soil and usually taken up by opening disc, gauge wheels and closing wheels. Opening disc and closing wheels utilize certain amount of pressure to create and cover the seed trench. Due to variability in actual field conditions, requirements of opening disc load vary. Gauge wheels carry excess load from applied downforce and prevent the opening disc to get deeper depth. Pressure that is applied on gauge wheels to remain in contact with ground for maintaining desired seed depth is GWL margin. It is vital to have consistent margin that ensures uniform seed depth which ultimately affecting emergence and yield. Also, consistent margin leads to improved soil contact, reduce compaction and sidewall smearing. Therefore, this study aims to investigate under which conditions consistent margin is implemented in active control system of the planter. Does consistency in margin leads to consistency in seeding depth. An experiment was conducted to evaluate the effect of four downforce margins 445N, 778N, 1112N and 1446N and three planter speeds 8, 12 and 16 km/h on planting efficiency. Depth and acceleration measurements were taken in a randomly selected 5.33-meter strip of each planter pass. Statistical techniques such as linear regression model and data visualization were used to quantify the impact of various independent variable on GWL. Results indicated that higher gauge wheel margin specifically 1112 N had lower variability (30%).

Also, higher gauge wheel margins resulted in better seed depth consistency. Gauge wheel margin consistency was significantly influenced by seeding depth, planter speed and acceleration at 95% confidence interval. Implementing, monitoring and managing gauge wheel margin within certain variability can provide greater seeding depth consistency.

INTRODUCTION.

Planting is one of the consequential agricultural operations that optimize field production. The primary objective of planting is to place seed consistently at an accurate seeding depth that ensures both seed to soil contact and uniform spacing (Hudspeth and Wanjura 1970, Nielsen, R. L. 2005, Zhao and Chen, 2015). Achieving uniform seeding depth is important for stand establishment, healthy crop growth and ultimately maximizing yield potential (D. Karayel and A. Özmerzi, 2008). Proper seed placement at its intended target depth exposes seed to the correct amount of moisture, aeration and temperature which provides favorable germination conditions (Badua et al., 2021; Poncet, 2016; Poncet et al., 2019; Virk, 2020). Furthermore, accuracy in seeding depth helps to minimize the risk from surface level hazards such as crusting, pests, or desiccation. Even small deviations in seeding depth such as planting a half inch shallower or deeper than the target can cause uneven emergence and hinder early crop development.

Studies have shown the consequences of improper seed depth. Planting shallower than optimal depth leads to drying out of seeds as they fail to access sufficient soil moisture from upper soil layers while planting deeper results in delayed emergence and reduced seedling vigor as they struggle to meet their oxygen requirements and expend more energy pushing through soil (Li et al., 2023). Both cases would result in uneven stands because some plants would get competitive advantage while others lag behind. This inconsistency weakens the stand establishment, and it creates uneven competition for light, nutrients and water across the season. Depth uniformity provides an optimal environment for emergence (S. Badua et al., 2019; Kimmelshue et al., 2022). Emergence uniformity has been shown to exert a notable effect on yield, though its magnitude varies with crop type and soil conditions. In corn (*Zea Mays* L.) depth does not only impact germination but also strongly affects root development and subsequent plant growth (Warren et al., 2019). Liu et al., 2004 showed corn yield has increased as much as 4-10% with uniform

emergence. These findings highlight that seeding depth is a critical parameter for evaluating plant quality and maximizing yield.

With the aim of optimizing crop productivity, farmers are increasingly adopting precision agriculture technologies such as precision planters to improve seed placement accuracy. Precision planting systems ensure consistent depth, spacing, and rate of seed placement across varying soil conditions. Multiple components of precision planter function together to achieve consistent seed depth. First, row cleaners clear the residue from the surface to create a clean path for seed placement, hence minimizing residue interference. Second, opening disks engage the soil to cut a precise trench into which seed is delivered by seed metering system (Li et al., 2023; Sharda, 2017). Once the trench is created, gauge wheels come into play. Gauge wheels regulate how deep the opening disk penetrates by maintaining contact with soil surface. Among all the components, gauge wheels are particularly critical in determining seed depth consistency. The load carried by gauge wheels typically known as Gauge Wheel Load (GWL), must be carefully managed. Insufficient GWL would lead opener disks to ride in an upward direction which results in shallow planting. On the other hand, excessive GWL compacts the seed zone and restricts seedling emergence. Thus, the interaction of gauge wheel load with other planting components governs depth consistency across fields (Murray et al., 2006).

To achieve seed depth consistency in varying soil conditions, precision planters are increasingly equipped with active control systems that integrate real-time sensors, automated controls, and hydraulic downforce adjustment (Badua et al., 2024). Active downforce control system regulates GWL in real time which accounts for spatial variability in soil properties. The applied downforce typically consists of the row unit's own weight combined with additional load applied through a hydraulic system, especially in planters equipped with individual row hydraulic downforce (IRHD) (Sharda, 2017). In practice, the operator sets a target GWL, or downforce, and the system automatically adjusts as conditions change. This adjustment is essential because opener disks require more force to penetrate harder soils while in softer soils excessive pressure can lead to compaction (Badua et al., 2018; Badua et al., 2021). This dynamic adjustment allows opener disks and gauge wheels to stay properly engaged with the soil, even as field conditions vary within and across planter passes.

Experimental evidence highlights the agronomic impact of balancing target GWL. Poncet et al. (2018) evaluated corn planting using three seeding depths (44 mm, 70 mm, and 95 mm) and

three downforce settings (0 N, 1100 N, and 1800 N) treatment in strip-tilled fields with silt-loam and sandy-loam soils. The findings showed that a seeding depth of 44 mm with a row-unit downforce of 1200 N created the most favorable conditions for uniform emergence in their environment. Hanna et al. (2010) investigated three GWL treatments low (335 N), medium (690 N), and high (>890 N) in no-till corn planted field which had silty-clay-loam soil. Their findings showed that excessive GWLs above 890 N led to deeper seed depth than the target depth, which indicates the tradeoff between adequate soil penetration and over-compaction. From a mechanical standpoint, row unit downforce is apportioned among planter's soil engaging components such as opener disks, closing wheels, and gauge wheels (Badua et al., 2018, 2021). A fixed portion is used for trench covering, another portion is consumed by opener penetration, and the remainder supports the gauge wheels to maintain target depth (Badua et al., 2018, 2021, 2024). Opening disc encounter soil penetration resistance due to varying soil conditions such as soil texture, moisture, topography, prior compaction from machine operation or field history, etc. When opener disk penetration requires more force than the row-unit weight and available hydraulic support, the system reallocates excess load from the gauge wheels, which risks shallow planting if gauge wheels lose soil contact. To avoid this, IRHD systems automatically provide additional load from the toolbar to individual row unit that ensures opener disks penetrate adequately while gauge wheels remain engaged with the soil. In this way, IRHD balances competing demands of soil engagement components to achieve consistent depth and optimal seed-to-soil contact (Hanna et al., 2010; Badua et al., 2024).

Despite these technological advances, achieving consistent seeding depth in the field remains challenging. Within-field variability in soil texture, compaction, and moisture means that the optimal downforce in one zone is unsuitable in another. Low downforce prevents opening disk to penetrate in hard soils hence it led to shallow planting whereas, high downforce causes over-compaction in soft soils, altering seed placement, restricting emergence and root growth. Farmers often compensate for this by reducing planting speed, but even at slower speeds inconsistent stands can persist. Also, there is an absence of explicit metrics or feedback mechanism for setting GWL margins. Operators usually set margin experience, trial-and-error, or manufacturer's recommendations, which may not always reflect field conditions. While IRHD systems sometimes provide indirect measures such as ride quality, they do not explicitly indicate whether the selected

margin ensures consistent depth. As a result, operators adjust based largely on visual cues or instinct rather than feedback from a closed-loop system.

This uncertainty underscores the need for research on GWL margin settings under real-world variability. There is limited knowledge on how target GWLs should be adjusted in response to planting speed and field variability to achieve depth consistency. Farmers frequently select one GWL setting for an entire operation or make iterative adjustments without clear evidence of its effectiveness. Consequently, gaps remain in understanding how GWL interacts with planter speed to influence seeding depth uniformity. Therefore, the objective of this study was to quantify gauge wheel load (GWL) variability and its relationship with seeding depth uniformity when operating at different target GWLs and planting speeds, and to examine variation of GWL across different planter sections.

Materials and Methods

Study area and crop description

This study was conducted in 2023 at Clay Center, Kansas (39.348993°, -97.179073°). The experimental treatments were applied only to 12.29 hectares where the total planted area was approximately 85.32 hectares. The field was managed using a pivot irrigation system, and no till farming techniques were adopted. The study area was under a crop rotation cycle of soybeans (*Glycine max* L.) and corn from the beginning of Spring 2020. Apparent soil electrical conductivity (EC) measurements were taken using a DUALEM-1 EC sensor, which was attached to a John Deere 855d utility vehicle. On the planting day, nine soil samples were systematically collected from a depth of 305 mm with a Classic Soil Probe (Model L, Oakfield Apparatus, Fond du Lac, WI, USA), which has a 19 mm inner probe diameter. This method ensured that the sampling was evenly distributed throughout the field. The samples were then analyzed for soil texture at the Soil Testing Laboratory of Kansas State University. The results showed that the soil was mainly silty clay loam, with an average composition of 57.67% clay, 30.22% silt, 12.11% sand, and a moisture content of 24.93%. The soil taxonomy classification indicated 55.1% Crete silt loam, 0.5% Crete silty clay loam, and 44.4% Geary silt loam. On April 24, 2023, Corn (*Zea mays* L.) hybrid corn seed 214-78DGV2T2 PRIB CHANNEL BIO was planted in an experimental area at a seed rate of 67954 seeds/ha. Field planting was carried out with a John Deere 1775 NT

24-row-30 planter, which has 24 row units spaced 762 mm apart. During planting, a solution of Ammonium Polyphosphate (10-34-0) was applied in-furrow at a rate of 32.27 l/ha, utilizing the planter's built-in fertilizer delivery system.

Row crop planter

Planting was carried out with a John Deere 1775 NT 24-row 30 planter, which has 24 row units spaced 762 mm apart as shown in Figure 2.1. The planter was operated by a John Deere 8R 410 tractor and managed using a SeedStar™ 4HP planting monitor (Deere & Company, Moline, IL, USA). It featured ExactEmerge™ row units that used a BrushBelt™ trench delivery system to move seeds from the meter to the furrow. Each row unit was equipped with an electric drive metering system for accurate seed delivery. During the experiment, IRHD control actively managed GWL for each row unit. A target planting depth of 50.8 mm was set for each row unit using a calibration tool (Set-N-Seed), Graphite seed flow lubricant Talc 80/20 was applied at a rate of 38 grams per 80,000 seeds (Talc U.S.A. 2023). The row cleaners were adjusted to a light-medium setting, and the closing wheels were positioned in the "C" setting, which was suitable for the field conditions. A custom data acquisition system was created to monitor and log real-time planting parameters. Only the odd-numbered row units (12 out of 24) were fitted with hydraulic pressure transducers (HAD 846K-A-5000-000, HYDAC, Glendale Heights, IL, USA) to measure real-time hydraulic oil pressure. These measurements helped determine the actual downforce exerted by the hydraulic system on the row units to achieve the desired GWL (GWL) during planting. Additionally, these row units were equipped with accelerometers (Model 3741E1210G, PCB Piezotronics, Depew, NY, USA) to track vertical acceleration during planting. The measurement range of accelerometers is 0-10G, where G is gravitational acceleration. Location and travel speed were recorded using a sub-inch accuracy GPS unit (GR5, Topcon Positioning Systems, Inc., Livermore, CA, USA). The same row units also had factory-installed proprietary load cells to measure real-time GWL during planting. Data from the load cells, hydraulic pressure transducers, accelerometers, and GPS signals were captured using a custom LabVIEW (National Instruments, Austin, TX, USA) program through a control laptop computer (Latitude 3400, Dell, Round Rock, TX, USA) and a NI cRIO chassis via C Series modules (National Instruments, Austin, TX, USA) at 100 Hz sampling frequency and down sampled within the LabVIEW to 10 Hz to record in *.csv file.

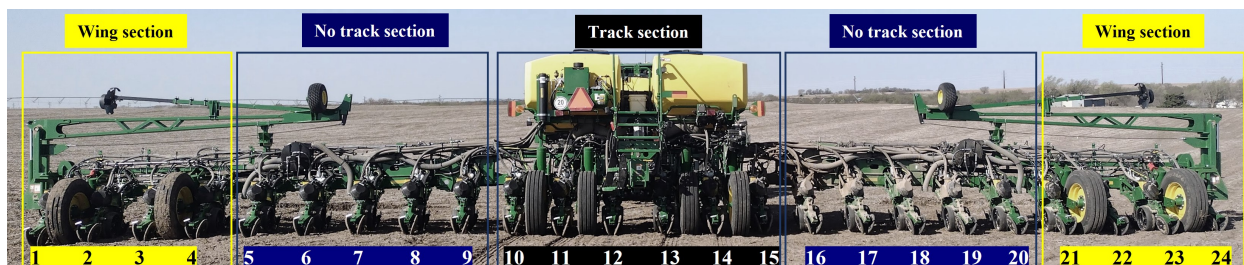


Figure 2.1 Precision planter

Experimental Design

A field experiment was conducted using a 24-row precision planter operated in a serpentine pattern across the study area. The four planter runs were pre-assigned for fixed downforce settings of 445, 778, 1112, and 1446 N, respectively, and these settings were maintained consistently throughout the experiment. This configuration enabled simultaneous evaluation of the four downforce levels during each planter to pass across the field.

Planting speed served as the second experimental factor and consisted of three target levels: 5, 8, and 16 km h⁻¹. This arrangement generated a full 4 × 3 factorial combination of downforce and speed across planter passes.

Within each combination of downforce and speed, measurements were collected at three planter sections: Wing, Non-Track, and Track representing distinct row-unit positions relative to the toolbar geometry and tractor tire paths. These three sections provided three observational subsamples for every downforce–speed combination. Because the study objective was to characterize seeding depth variation and gauge-wheel load responses across planter configurations, the section-level measurements were treated as subsamples rather than independent treatment factors, and all section observations were retained to represent within-unit variability.

Overall, the experiment followed a factorial treatment structure (4 downforce levels × 3 planting speeds) with three subsamples per treatment combination, implemented across serpentine planter passes using a 24-row planter. All observations from the three sections were used for statistical modeling and analysis to quantify treatment effects and depth variability. A 5.33-meter-long experimental strip was randomly selected in each treatment, where measurements were taken.

Seeding Depth

The seed depth for each emerged plant within each experimental unit was measured manually at the V1 stage of the seedlings. This process involved determining the distance from the center bottom of the seed to the top of the soil surface. A wooden marker, measuring 2.75 millimeters thick (300 mm long and 28.18 mm wide), was placed across the direction of the planter's movement to mimic the pressure applied by the gauge wheels on the surface residue, thereby establishing an upper reference point. The depth was then recorded using a digital caliper (SYLVAC IP67, Malleray, Switzerland), which was positioned perpendicular to the wooden marker with the zero-mark aligned at the top.

Data analysis

Data analysis was conducted using python version 3.11.5 to comprehensively evaluate the variability of GWL, seed depth, and the impacts of different treatments on the performance of planting. The raw data was captured at 10 Hz through a purpose-built data acquisition system. Preprocessing the data was done to remove inconsistencies or missing values, and also appropriate transformations were carried out wherever necessary. Variables such as GWL, seed depth, speed, and acceleration were normalized to ensure comparable data across treatments. Descriptive statistics and visualization tools were employed to perform preliminary analysis. Using matplotlib and seaborn python packages, boxplots, density plot, and scatter plot were produced to determine the distribution and variability within and between treatment. This worked helped to identify the trends, outliers, and potential outliers, which made it simpler to know variable relationships before applying complex models. A multiple linear regression model was applied to estimate the effect of independent variables (speed, downforce, and depth) on GWL. This ensemble strategy enabled variable importance estimation and detection of intricate variable interactions. To ensure model reliability constructed for the dataset, the dataset was divided into training (85%) and testing (15%) sets.

$$GWL = \beta_0 + \beta_1(DF) + \beta_2(Speed) + \beta_3(Depth) + \beta_4(Acceleration)$$

Depth accuracy was evaluated by calculating depth bias as the difference between the measured seeding depth and the target depth of 50.8 mm (2 inches)

$$\text{Depth bias} = \text{Depth measured} - \text{target depth}$$

A negative value indicates shallower-than-target placement, whereas a positive value indicates deeper placement. To quantify how planter settings and dynamic sensor measurements influenced mean depth deviation, a multiple linear model was fit using depth bias as the response and downforce (DF), planting speed, acceleration and gauge wheel load (GWL) as predictors:

$$\text{Depth Bias} = \beta_0 + \beta_1(\text{DF}) + \beta_2(\text{Speed}) + \beta_3(\text{DF} \times \text{Speed}) + \beta_4(\text{Acceleration}) + \beta_5(\text{GWL})$$

Downforce and speed were treated as categorical fixed effects (DF = 445, 778, 1112, 1446 N; Speed = 8, 12, 16 km h⁻¹). Acceleration (G) and GWL (N) were included as continuous covariates to represent real-time mechanical loading and row-unit motion. Model fitting was performed using the `lm()` function in R programming. Type III ANOVA was used to assess statistical significance of main effects and interactions, and model coefficients were used to quantify direction and magnitude of effects. Significance was evaluated at $\alpha = 0.05$.

To evaluate factors influencing variability in seeding depth, a second model was developed to quantify how downforce (DF), planting speed, acceleration (ride quality), and gauge wheel load (GWL) affected the variance around the target depth, rather than the mean deviation. Variance was modeled using the squared residuals obtained from the depth bias model. First, the predicted deviation from the 2-inch target was estimated using the depth bias linear model. The residuals from this model represent the unexplained variation in depth for each observation. These residuals were squared to produce a variance-like measure for each planting instance.

Because variance values are non-negative and often right-skewed, the squared residuals were log-transformed to stabilize variance and approximate normality. The resulting variable, `log(resid_sq)`, was used as the response in a linear model including DF, Speed, Acceleration, GWL, and their interaction (DF $\times$ Speed). This approach follows standard variance modeling procedures, where predictors of instability (rather than mean shift) are identified. ANOVA was performed to assess the significance of main effects and interactions, and model coefficients were used to evaluate the direction and magnitude of influence.

$$\log(\epsilon_i^2) = \beta_0 + \beta_1(DF) + \beta_2(Speed) + \beta_3(Acceleration) + \beta_4(GWL) + \beta_5(DF \times Speed) + u_i$$

Where, ϵ_i^2 = squared residual (variance contribution), $\log(\epsilon_i^2)$ = log-transformed variance, u_i = residual error term, DF and Speed are categorical factors, Acceleration and GWL are continuous predictors

Results and Discussion

Depth accuracy using Mean deviation of depth from target depth

The depth-bias model showed that downforce, planting speed, and gauge wheel load (GWL) significantly influenced how far the achieved depth deviated from the 2-inch target. Downforce had a strong main effect on depth bias ($p < 0.001$), and planting speed also contributed significantly ($p = 0.017$), with faster speeds producing progressively shallower placement. Gauge wheel load was a significant positive predictor ($p = 0.013$), indicating that greater row-unit load resulted in deeper seeding. Acceleration did not significantly affect mean depth ($p = 0.214$), which is consistent with its role as a measure of vertical disturbance rather than a direct driver of systematic depth offset.

A significant $DF \times Speed$ interaction ($p = 0.0033$) showed that the effect of downforce depends on operating speed. As the combination of 1446 N at 12 km h⁻¹ produced significantly deeper placement, demonstrating that excessive downforce can lead to over-penetration at certain speeds. Under baseline conditions (445 N, 8 km h⁻¹), the planter placed seeds 0.48 inches shallower than the target. Increasing speed to 16 km h⁻¹ resulted in an additional 0.16-inch reduction in depth. The positive GWL coefficient (0.00032 in per N) reinforces that GWL represents the true soil row unit interaction force and is more directly tied to seeding depth than commanded downforce alone. Overall, the model explained 42.5% of variation in depth bias, indicating that downforce operational speed and real-time GWL measurements collectively drive depth accuracy. These results clearly demonstrate that maintaining appropriate downforce and adequate GWL is essential for achieving the intended seeding depth, while acceleration mainly affects depth stability rather than the mean depth itself.

Table 2.1. ANOVA table for Depth Bias

Response:Depth bias	Df	Sum sq	Mean sq	F value	P value
Downforce	3	1.4023	0.46744	10.3905	1.193e-05
Speed	2	0.4053	0.20267	4.5051	0.01777
DF:Speed	6	0.9560	0.15934	3.5419	0.007213
Residuals	94	4.6283	0.04821		

Variance Modeling for Depth

The variance model tested whether downforce (DF), planting speed, gauge wheel load (GWL), and acceleration influenced the stability of seeding depth, measured as the log-transformed squared residuals from the depth bias model. The ANOVA results (Table 2.2) showed that none of the factors significantly explained variation in depth variability. Downforce ($F = 1.67$, $p = 0.179$) and speed ($F = 0.09$, $p = 0.917$) did not affect the spread of depth around the target. Acceleration also had no significant effect ($F = 1.54$, $p = 0.218$), indicating that row-unit vibration did not translate into greater instability of depth placement. Gauge wheel load approached marginal significance ($F = 3.28$, $p = 0.073$), but the effect was weak and did not meet the $\alpha = 0.05$ threshold. The $DF \times Speed$ interaction was not significant ($F = 0.44$, $p = 0.850$), indicating that combinations of downforce and planting speed did not alter depth stability.

Overall, the model explained only 11.8% of the variability in log-residuals, and the overall model was non-significant ($p = 0.484$). These results indicate that while DF, speed, and GWL significantly affected depth bias, they did not significantly influence depth variance, meaning the planter maintained similar stability in depth placement across all treatments. In practical terms, operational settings affected how far the planter deviated from the target depth, but not how consistently it held that depth. Depth errors in this study were therefore primarily driven by mean offsets rather than instability, highlighting that accuracy is the main limitation when downforce margin and planting speed are mismanaged.

Table 2.2 ANOVA Table for Variance of depth

Source	df	Sum Sq	Mean Sq	F value	P value
---------------	-----------	---------------	----------------	----------------	----------------

DF	3	27.62	9.208	1.667	0.179
Speed	2	0.96	0.480	0.087	0.917
DF × Speed	6	14.62	2.437	0.441	0.850
Residuals	94	519.18	5.523	—	—

GWL CV and depth consistency

Figure 2.2 shows how the GWL margin varies with different applied downforce treatments. As the applied downforce increases from 445N to 1112N, the GWL also increases. It is inferred that the system is working correctly; the more applied downforce translates to more loads being carried by gauge wheels. However, the spread of GWL values increases in higher downforce settings. This shows inconsistency in the selected margin. The findings reveal that higher GWL margins 1112N, exhibited consistently lower variability, which is also indicated by the lower coefficients of variation in Figure 2.3. This reduced variability in GWL margins resulted in closer to target and more uniform seeding depth, which is essential for consistent crop establishment. The best depth consistency was noted at GWL margins of 778N and 1112N as illustrated in Figure 2.4, highlighting the significance of choosing the right GWL margins for optimal planter performance.

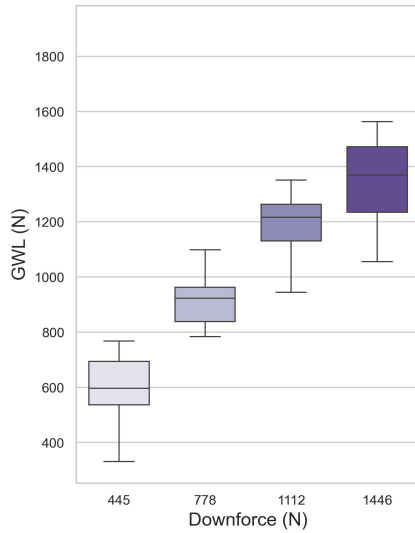


Figure 2.2. GWL v/s Downforce

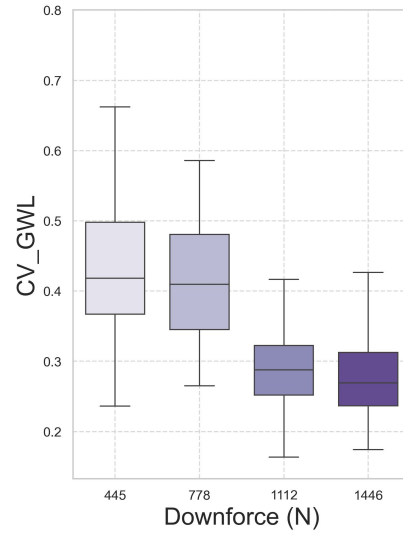


Figure 2.3. CV GWL v/s Downforce

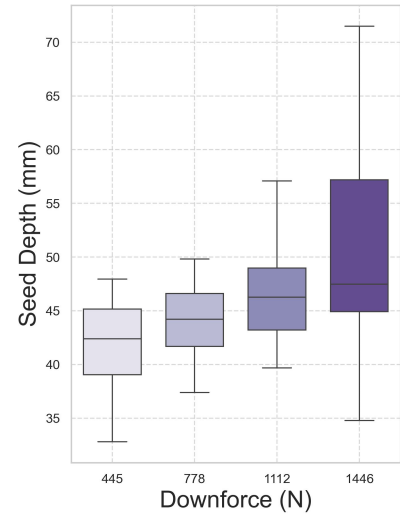


Figure 2.4. Seed Depth v/s Downforce

Influence of different variables on GWL

Seeding depth plays a vital role in successful crop establishment, as it influences the contact between the soil and seed, which in turn affects the germination rate. Notably, a 0.25 unit increase in seeding depth resulted in a 35-unit increase in GWL margin. GWL margin and seeding depth have positive correlation at all three speeds (Figure 2.5). This highlights the need to optimize seeding depth to maintain a sufficient GWL margin and ensure proper contact between soil and seed. The observation that a greater GWL margin is needed for deeper planting indicates that more downward pressure from the gauge wheel is necessary to achieve the correct seed placement. By increasing the GWL margin, the planter can better navigate the resistance posed by the soil, especially in areas that are dense or compacted. This enhanced soil contact leads to more uniform germination, which is essential for achieving optimal crop stands and maximizing yield potential. Therefore, farmers need to carefully adjust target GWL according to field conditions to maintain an appropriate seeding depth and optimal seed-to-soil contact.

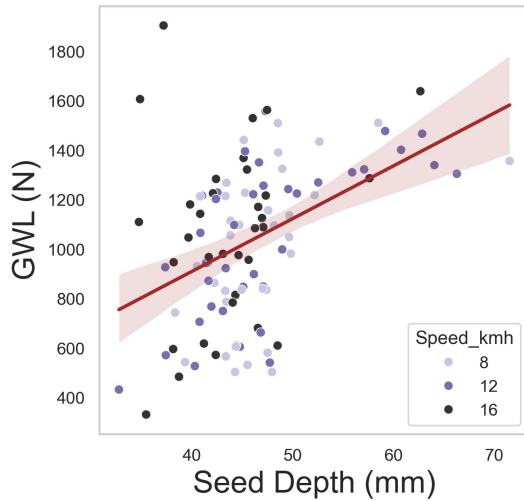


Figure 2.5. GWL v/s Seed depth on varying speed

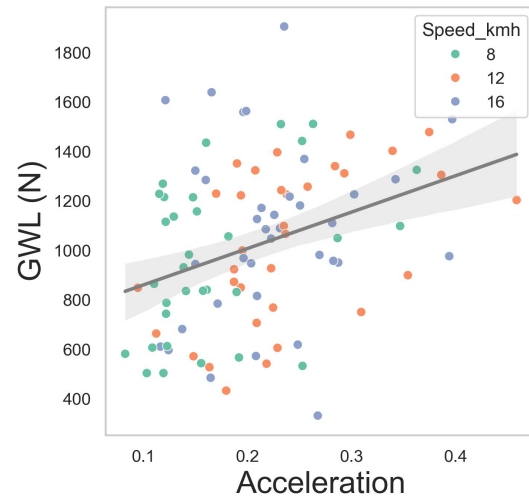


Figure 2.6. GWL v/s acceleration on varying speed

Acceleration is also an important factor in riding quality. However, it is not statistically significant to study its impact on GWL ($p=0.51$) at 95% confidence interval but at 90% confidence interval it is statistically significant. For every 0.1 unit increase in acceleration, an additional 8.4 units of GWL margin is required to maintain ground contact. For all three speeds, GWL margin and acceleration showed a positive linear relationship when one increases the other also increases (Figure 2.6). This indicates that higher accelerations require a higher GWL margin to ensure stability and consistent planting depth in rough field conditions or uneven terrain. Variations in planter movement caused by uneven terrain and field obstructions can lead to inconsistent seeding depth if the GWL margin is not adequate to keep ground contact steady. By adjusting the GWL margin to account for decreased accelerations, the planter can better handle these variations, minimizing the chances of shallow planting or seed exposure. This underscores the necessity of monitoring and managing ride quality to achieve uniform seeding depth, especially in fields with irregular surfaces.

The speed of the planter also had an impact on the GWL margin. Although the impact was not as significant as seeding depth and acceleration. For every 1 unit increase in planter speed, there was an 8-unit rise in the target GWL. This suggests that operating at higher speeds requires larger GWL margins to mitigate the effects of increased mechanical vibrations and potential instability of the planter. Faster speeds can cause more vertical movement, which may disrupt the

consistency of seeding depth. By adjusting the GWL margin upward at these higher speeds, the planter can maintain a more consistent depth, enhancing the accuracy of seed placement. However, if speeds become too excessive, it can still result in poor ride quality, highlighting the importance of finding a balanced strategy for managing both planter speed and GWL margin settings.

These relationships illustrate the intricate balance between seeding depth, acceleration, and speed in optimizing GWL. Properly calibrating these parameters is crucial for achieving consistent seeding depth and reducing variability, both of which are vital for ensuring uniform crop emergence and maximizing yield potential. Farmers should consider the specific conditions of their fields, such as soil type, terrain, speed, and the desired planting depth, when setting the optimal GWL margin. This approach will help ensure that the planter functions efficiently, with minimal variability in seeding depth, ultimately resulting in more uniform crop stands and increased yields. The linear regression equation to optimize GWL is

$$GWL = -100.325 + 7.7283 \text{ Speed} + 141.04 \text{ depth} + 84.521 \text{ Acceleration}$$

Ride quality and its relationship with GWL margin

Ride quality is important to the overall performance of planters, particularly in relation to the consistency of the placement of seed depth. The data illustrated that as planter speed increased so did ride quality, more adversely at higher speeds and with greater GWL margins (Figure 2.8). The combination of increased planter speeds and higher GWL margins increased the variability of the acceleration which confirm the importance of achieving optimized speeds with stable ride quality. Ride quality deterioration at increased planter speeds can create a situation of inconsistent seed placement resulting in poor crop emergence and ultimately reduced yields.

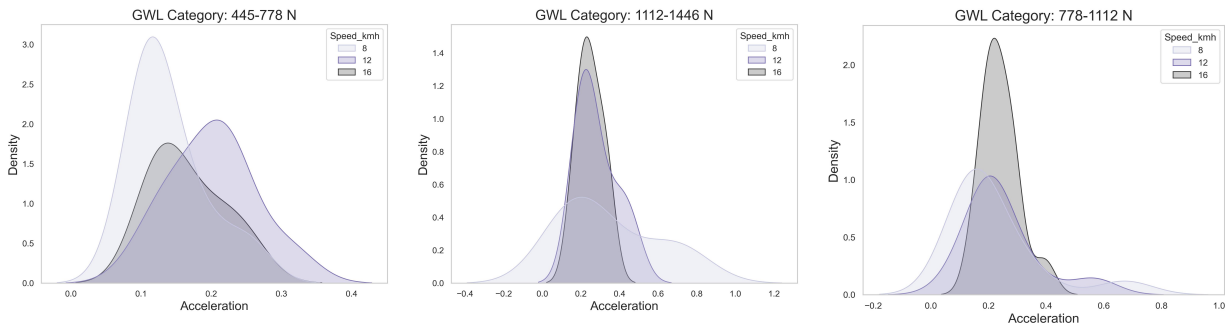


Figure 2.7. GWL margin variation with acceleration on varying speed

Speed of planter interaction with GWL Margin

The integration of statistical modeling and graphical analysis revealed clear differences in gauge-wheel load (GWL) behavior across the evaluated downforce margins. The objective was to identify a downforce setting that maintains stable gauge-wheel soil contact across operating speeds while minimizing both under- and over-loading of the row-unit conditions that directly impact seeding depth accuracy. The combined evidence indicates that the intermediate downforce setting (778 N) provided the most balanced and agronomically desirable performance across field speeds.

At the lowest margin (445 N), GWL exhibited strong sensitivity to increase in planting speed. Model outputs showed that GWL increased by approximately 63 N when speed increased from 8 to 16 km h⁻¹, and the boxplots (Figure. 2.10) revealed extremely wide distributions at the highest speed. This behavior indicates that the gauge wheels were frequently losing and regaining contact with the soil surface, producing abrupt fluctuations in load. Such instability is symptomatic of under-margining, where the applied downforce is insufficient to stabilize row-unit motion, resulting in inconsistent gauge-wheel engagement and greater risk of shallow or variable seeding depth.

In contrast, the highest margins (1112 N and 1446 N) maintained high absolute loads but displayed mechanical limitations at elevated speeds. At 1112 N, increasing speed to 16 km h⁻¹ produced a net decrease in GWL (-19 N), driven by a significant negative interaction effect between speed and downforce. This reduction reflects partial unloading of the gauge wheels, likely caused by restricted vertical travel of the row-unit under excessive downforce. Similarly, the 1446 N setting maintained high median loads but showed reduced responsiveness and greater variability at high speeds, indicating that overly aggressive downforce can constrain gauge-wheel motion and diminish its ability to follow soil micro-topography. Both high-margin conditions therefore risk reduced depth accuracy not due to insufficient load, but due to impaired mechanical compliance and potential soil compaction.

The most favorable behavior occurred at the intermediate margin (778 N). At this setting, changes in planting speed produced only small changes in GWL (12 N increase at 12 km h⁻¹ and 3.5 N at 16 km h⁻¹). The boxplot distributions were narrow and stable across speeds, indicating that the gauge wheels maintained consistent soil contact without the excessive oscillation observed

at lower margins or the mechanical restriction observed at higher margins. The depth-bias model further supported this observation, showing improved stability of depth placement compared with both low and very high margin treatments. Collectively, these results demonstrate that 778 N provided the most robust response across the tested operating conditions, balancing GWL magnitude with mechanical stability and responsiveness.

Table 2.3 Speed Interaction with Target margin

Source	df	Sum Sq	Mean Sq	F value	P value
DF	3	369613	123204	68.1840	2e-16
Speed	2	5349	2675	1.4802	0.23274
DF × Speed	6	21367	3561	1.9708	0.07732
Residuals	96	173466	1807	—	—

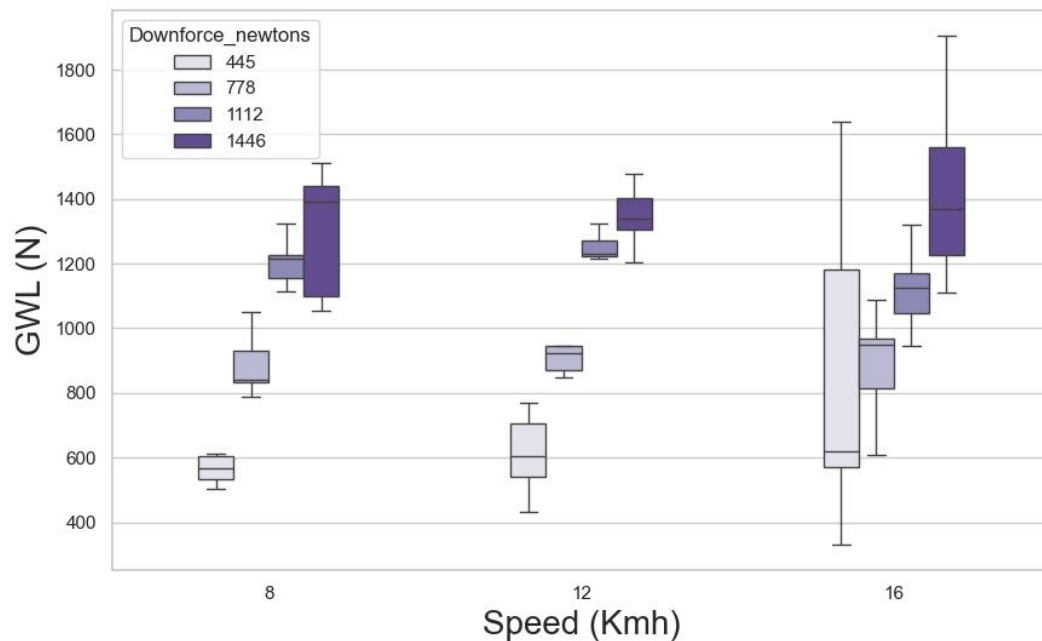


Figure 2.10. Speed interaction with GWL margin

Sectional GWL variation across planting speeds

The density distributions comparing gauge wheel load (GWL) at three operational speeds (8, 12, and 16 km h⁻¹) reveal variation in variability of load across planter sections (Wing, Track, and Non-track rows).

At 8 km h⁻¹ there is considerable overlap in GWL distributions across all three planter sections, and peak densities are located approximately near 1000 N (Figure 2.12). Variability across the toolbar is low; except in non-track rows, there is a concurrent shift toward lower GWL values than the track and wing rows. Thus, at slow speeds, the intended applied downforce appears to be successfully matched with uniform GWL across planter sections.

At 12 km h⁻¹ there are more apparent section differences. The track rows maintain a narrow distribution and peak density near 1000-1200 N (Figure 2.13). The wing rows show a broader distribution, have higher peak density, and are much more dispersed in both lower and higher GWL values along the x-axis. The non-track rows also indicate a slight shift toward lighter GWL. This indicates that as operational speed increased, the planter sections began to respond differently to field conditions, and the wing rows exhibited less stability.

At the highest speed examined, 16 km h⁻¹, the sectional divergence was at its greatest (Figure 2.14). The wing rows showed the greatest range of load distribution, with nearly a 2500 N range from <500 N to >2000 N, implying a significant degree of instability to maintain the target GWL. The track rows sustained higher loads, but loads were concentrated close to the mean, while non-track rows showed intermediate behavior but were trending toward below baseline GWL compared to track rows. However, there are clearly larger differences in load distribution as speeds increase, especially with wing sections where instability is greatest.

Overall, these results suggest that planting speed is an amplifier of sectional differences in GWL, while at lower speeds, some control of correct GWL load was maintained throughout the planter frames. Higher planting speeds induced a greater divergence of GWL due to greater section movement that could not keep wing rows in contact with the ground. It is reasonable to assume that this divergence of GWL load across planter sections, in higher speed operation, results in a non-uniform loading that partially accounts for inconsistent depth control and non-uniform seed placement. This highlights the need for speed-sensitive, downforce management strategies in modern planter systems.

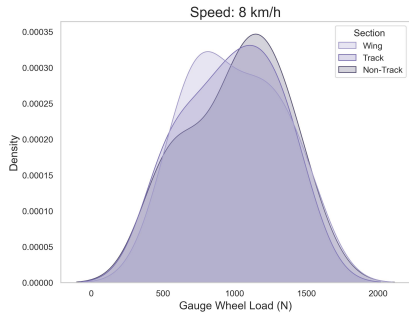


Figure 2.6 Sectional graphs for 8 km/h

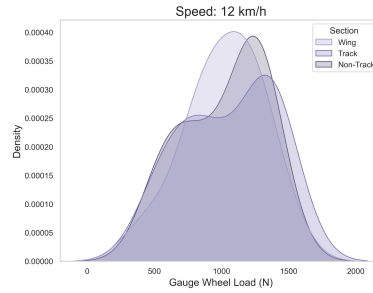


Figure 2.7 Sectional graphs for 12 km/h

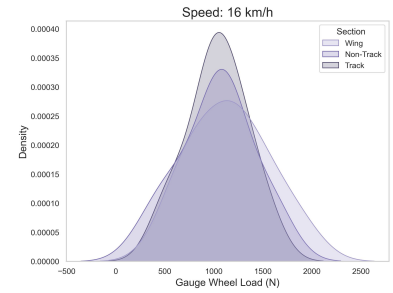


Figure 2.8. Sectional graphs for 16 km/h

Conclusions

This study identified the importance of a consistent gauge wheel load (GWL) margin in achieving consistent seed depth and improving seed-to-soil contact, especially under changing soil texture and changing terrain. There was a statistically significant influence of seeding depth, planters speed, and acceleration on the GWL margin, and seed depth was the most influential variable. Higher GWL margins were associated with less variability, increased depth consistency, and more uniform emergence, all of which eventually contributed to yield potential. The best planter performance was observed when GWL margins were maintained between 778–1112 N, especially under moderate operating speeds.

The interaction between planter speed and downforce was particularly important. At lower planter speeds, low downforce settings were sufficient to maintain stable GWL. However, as operating speed increased, variability in GWL rose sharply at lighter margins, indicating loss of consistent soil contact and increased risk of shallow placement. Only higher margins were able to sustain relatively stable GWL under high-speed operation, underscoring the need for speed-sensitive GWL management strategies.

Analysis across planter sections further revealed that GWL distribution was not uniform across the toolbar. At lower speeds, wing, track, and non-track rows maintained similar load distributions. As speed increased, however, wing rows showed the greatest instability and broadest variability, while track rows maintained higher and more consistent GWL values, likely due to soil compaction from tire tracks. These results demonstrate that planter section interacts with speed to influence GWL margin stability with wing sections being most vulnerable to inconsistent seed placement at higher planting speeds.

The findings emphasize that optimal planter performance requires careful balancing of speed and GWL settings to ensure smooth operation, stable ride quality, and consistent planting depth. GWL margin is not only selected based on planting depth, speed and acceleration but also with planter section in order to achieve the seed depth consistency. This enables farmers to make more data-driven management decisions during planting operations.

In the future, this work should entail the development of real-time calibration and decision-support tools that use soil properties, operating speed, and machine behavior to assist in GWL margin modification. This will advance planter performance even further, reduce variability in depth and emergence, and potentially increase yield conditions in situ.

Chapter 3 - Quantifying emergence uniformity using E-Depth in seeding system

ABSTRACT

Uniform crop emergence is a critical factor in maximizing yield potential in row crop production systems. This study evaluates the effect of seeding depth on emergence uniformity and yield performance using an electronic depth control (e-Depth) system integrated with a precision planter. Field experiments were conducted over two growing seasons under varying field conditions. Three seeding depth treatments (1.5", 2.0", and 2.5") were implemented using an unbalanced randomized complete block design with replications. Data were collected on seedling emergence, actual planting depth, grain yield, and environmental variables including soil temperature, GDD. Machine Learning models such as Logistic regression, ANOVA and data visualization techniques were employed to assess the relationships among planting depth, emergence uniformity, and yield outcomes. Results indicate that a 2.0" seeding depth consistently produced improved emergence uniformity and was positively associated with yield across varying field regimes. The objective of this research is to quantify deviations in emergence uniformity as influenced by planting depth and determine their implications on yield. Findings from this study offer actionable insights for producers seeking to optimize field-specific seeding depth using data-driven tools to enhance stand establishment and maximize yield potential

Introduction

Optimizing cropping practices using technological advancements is critical for corn (*Zea mays* L.) production in the United States. As corn production in 2025 is expected to reach 16.7 bushels exceeding 2024 by 13 percent which would be highest grain production on record of United States. Technological advancements in precision planters have enhanced the capability of planting systems to maximize production. The ultimate goal of using high-end technology is to maximize yield. Corn yield is forecasted to record 188.8 bushels per acre, which is a 9.5 bushel per acre increase from last year (USDA, NASS, 2025). Studies have shown that corn vegetative development depends upon how accurately the seed is placed in the soil for a particular hybrid, soil type and prevailing environmental conditions (S. A. Badua et al., 2021). For this purpose, the

most important decision a farmer makes while planting corn is deciding its seeding depth. Planting at appropriate depth maintains optimal seed to soil contact that ensures seeds absorb soil moisture for germination. Corn germination is majorly dependent on water imbibition, and this occurs when seed zone soil temperatures are in the range 50-65 degrees F (Stewart et al., 2021).

Corn seeds lose their ability to withstand cold stress as they absorb water because the vigor of the seedlings is diminished by cold water. Chilling injury can be prevented by soil temperatures greater than 50°F and a favorable weather forecast for the 24 to 48 hours following planting (Stoll & Saab, 2014). Slow germination, physiological abnormalities, and seedling death are caused by cool temperatures and conditions of excessively wet or dry moisture (Hoeft et al., 2000). Along with soil moisture and soil temperature soil characteristics such as soil texture and bulk density influence the germination process (Hadas, 2004). Soil temperature and water content are significantly influenced by the texture, or the percentage of sand, silt, and clay in the soil particle size composition (Brady & Weil, 2002). When planting is followed by a heavy rain that damages the soil structure, seedling emergence in clay soils may be decreased. This leads to soil crusting which can be describes as a compacted or sealed soil surface layer (Parker & Taylor, 1965). Less water may be available to seeds in these circumstances, and they may not have enough force to break through the soil's surface (Hadas, 2004). Traditional practices such tillage also influence the above-mentioned soil properties. Dam et al. (2005) found that emergence rate was slower at no tillage relative tilled field. Additionally, crop residues can have a negative impact on corn emergence as hinders the seed to soil contact (Swan et al., 1996).

If planting is done at too shallow depth, then some plants would emerge faster but, in many cases, seeds would dry out and do not emerge at all (Sharda, 2017) Shallower planting may result in stunted root development as the crown region and nodal roots would be exposed to warm temperatures that cause damage and drying out (Warren et al., 2019). On the other hand, if seeds are planted too deep then it will take more energy to emerge that may lead to delayed emergence. Deeper seeds are susceptible to fungal diseases due to low soil temperatures at deeper depths (Warren et al., 2019). To improve the success of crop establishment, it is necessary to maintain optimal depth uniformly (A. Poncet, 2016).

At the time when depth is accurate but inconsistent, this may result in uneven emergence. A reduction in total crop yield is the most significant consequence of uneven emergence (Bob and Nielsen, 2005.; Dufour and Dufour, 2021; Li et al., 2023; Liu et al., 2004). Studies revealed that

in comparison to full stands of normal emergence, yield was reduced by 6 to 9% when there were sporadic emergence delays of roughly 10 days spread out across the field. Depending on how many delayed emergers there were compared to normal emergers, a 21-day delay in emergence decreased yield by 10 to 22 percent (Nielsen, 2005.). In this case competition between early emerged and late emerged for the water, nutrients and sunlight would increase and hence it would negatively impact late emerged plant. One out of every six plants experiencing a delay of two leaf stages reduced yield by 4%, and a four-leaf stage delay reduced yield by 8% (Liu et al., 2004, Novak and Ransom, 2018). According to literature, uniform emergence in corn can boost yield by up to 4% to 10%. Hence, Corn is especially sensitive to non-uniform emergence (Carter et al., 1989; Liu et al., 2004, A. M. Poncet et al., 2018). Therefore, it is important to place seed at appropriate seeding depth in order to get uniform emergence.

Under most field conditions, the recommended corn planting depth in Kansas is 1.5 to 2.5 inches which balances temperature, moisture content, and seed-to-soil contact for consistent emergence. Corn emergence and germination rates are strongly influenced by soil temperature and planting depth. While seedlings can emerge in 8–10 days at 60–65°F (15–18°C), corn may take 18–21 days to emerge at 50–55°F (10–13°C) (K-State, 2019). Low metabolic activity and cold stress cause little to no germination below 50°F. Deeper planting can postpone germination and increase vulnerability to seedling diseases or insect damage because deeper soils are colder. In contrast to deeper placements, early spring plantings when soils are still cool perform better at shallower depths of 1.5 to 2.0 inches, encouraging quicker and more consistent emergence. In contrast, 2 to 3 inches of planting depth are frequently needed for sandy soils, which warm more quickly but hold less moisture, in order to avoid seed desiccation in dry post-planting conditions. Any soil type may result in poor emergence and decreased stand density if plants are planted deeper than 3.5 inches (Kansas Corn Management 2025.).

Decisions about where to plant seeds are frequently made more difficult by precipitation variability during the planting season because shallow planting may not guarantee enough moisture for germination. The ideal planting depth is significantly influenced by soil characteristics like texture, organic matter, tillage, and drainage (Cox and Cherney, 2015). Soil temperature and moisture are two major factors that affect germination and emergence uniformity (Alessi and Power (1971), Alm et al. (1993), Dwyer et al. (2000), and Forcella et al. (2000)). Because mesocotyl and coleoptile must elongate further to reach the surface, planting too deeply

may delay emergence even though it can improve moisture and temperature stability in the seed zone (Blacklow, 1972). Increasing depth can slow emergence in addition to lowering temperatures. Controlling planting depth is therefore essential for consistent corn establishments in order to balance moisture and temperature.

Seed depth consistency may be improved by modern precision planters with seed firmer and active downforce control system. However, initial assessment may still be required to decide the proper depth (Badua et al., 2021; Virk et al., 2020). Previously, depth was set using T-Handles in planters. But in modern planting technology, modern precision planters are equipped with electronically controlled depth where a user can set depth in real time while working in the field without any manual calibration and hindering the planting process in the field. This system not only helps in reducing manual calibration of depth settings using T-handles but also reduces time in adjusting depth settings that encourages users to adjust depth in real time to incorporate the soil variability. To maximize emergence uniformity, it is critical to ascertain how soil temperature and moisture at varying planting depths affect emergence, growth, and yield. Planting operations can incorporate field variability which may result in uniform stand. Despite available technology, real-time planting depth adjustment is still a challenge due to insufficient data and research to claim its efficacy in actual field conditions. Its efficacy is dependent on how well the Edepth system works in field and how its use can be advantaged while implementing agronomic implication in deciding varying depth within the field to account for within field variation. Utilizing planting technologies that permit variable planting depths during the planting operation may be made more efficient if we have a better understanding of how corn responds to planting depth across various soil types and conditions. Thus, research is needed to evaluate the working of Edepth system and if Edepth is effectively working for real time adjustment of planting depth then quantify relationships/ conditions of emergence uniformity with different target depth under varying field conditions and its response on yield. Therefore, objective of this study was

1. Does changing depth maintains depth accuracy while running an electronically controlled depth system
2. Quantify emergence uniformity when planting corn at different depth at varying field conditions using electronic-depth control system
3. Evaluate Yield response to variable depth and emergence uniformity

Material and Methods

Site Description

This experiment was conducted in planting season for two consecutive years 2024 and 2025 at Clay Center, Kansas. Two fields with varying soil conditions were selected each year. The fields were managed using No-till farming techniques. Each year one field was irrigated using a pivot irrigation system, and the other was dryland. However, during 2025 planting season fields had wet conditions due to ongoing precipitation. In 2024, Field A (Kopfers) (39.350718,-97.174166) and Field B (TownsEnd) (39.205242,-97.27831) were planted with corn (*Zea mays* L.) hybrid corn seed DEKALB: DKC65-95RIB in 53 ha and 24 ha experimental area at the seed rate of 56833 and 59304 seeds per hectare respectively. The USDA Web Soil Survey (WSS) was used to determine soil properties. The Soil taxonomy of Field A was 45.8% Crete silty clay loam, 1 to 3% slopes; soil code 3828, 28.2% Crete silty clay loam, 3 to 7% slopes, eroded, loess plains and breaks; soil code 3820, 9.2% Hobbs silt loam; soil code 3545(USDA-NRCS (2023)). Field B was 49.8% Muir silt loam; soil code 3775, 32.9% Hobbs silt loam; soil code 356, 17.1% Geary silt loam; soil code 3844 (USDA-NRCS (2023)). In 2025, Field C (Griffiths Pivot South) (39.411022,-97.219528) and Field D (R&R) (39.309711,-97.146561) were planted with corn seed hybrid DEKALB: DKC65-95RIB and PIONEER: P1548AM-NI62 in 36 hectare and 32 hectare experimental area at the seed rate of 69188 and 59304 seeds per hectare respectively. Soil taxonomy of Field C is 98.3% Huscher silt loam; soil code 3580, Field D is 83.8% Crete silty clay loam; soil code 3838, 13.7% Crete silty clay loam; soil code 3830, 2.5% Hobbs silt loam; soil code 3561 (USDA-NRCS (2023)).

In Kansas, corn is usually planted from late March in southeastern counties to mid-May in northwest (Ciampitti, et al., 2024). This planting window varies every year due to uncertainty in weather conditions. Farmers usually plant on days other than optimal planting window due to excessive moisture in soil which is mainly a result of ongoing precipitation. (Badua, 2008). In order to plant corn, optimal soil temperature should be reaching 55 degrees Fahrenheit at a 2- inch soil depth for atleast three consecutive days (Ciampitti, et al., 2024). If ideal temperature conditions for germinations are not met, then seeds get susceptible to imbibitional chilling. Planting dates of 2024 growing season were April 12th (Field A) and April 15th (Field B); whereas for 2025 season planting dates were April 18th (Field C) and April 22nd (Field D).

Weather information for each planting season was obtained from Kansas Mesonet Weather data. Daily air temperature, soil temperature at 2-inch, and precipitation data from the day of planting for each of the fields were fetched. The daily air temperature data were then used to calculate the corn cumulative Growing Degree Days (GDD).

$$GDD = \frac{\sum_{i=1}^n T_{\max} - T_{\min}}{2} - T_{\text{Base}}$$

Where, GDD is cumulative corn growing degree days; $i = (1 \text{ to } n)$ represents the days from planting to the day where we had seen last emergence for each of the field; $T_{\max}$ is daily maximum temperature in Fahrenheit; $T_{\min}$ is daily minimum temperature in Fahrenheit.

Planting Equipment

Planting was performed using a John Deere 1775 NT 24-row 30 (Exact Emerge) planter operated with John Deere 8R 410 tractor and managed using SeedStar™ 4 HP planting monitor (Deere & Company, Moline, IL, USA) for both years (Figure 3.1). It was 24 row unit planter that was spaced 762 mm apart. The planter was outfitted with ExactEmerge™ row units and BrushBelt™ trench delivery for moving seeds from the meter to the seed trench. The rows had precision seed metering via electric drive systems. Row unit depth were adjusted using electronically controlled system (E-depth). Row unit downforce was controlled using Individual row unit hydraulic downforce system. Target Downforce margin for Field A was 890N; Field B was 890 N; Field C was 667N; Field D was 756N. Planter was operated at a speed of 12.07 Kmh. Graphite-talc seed flow lubricant (80/20 mix) was used to improve seed flow through seed delivery system in precision planter. Application of Ammonium Polyphosphate (10-34-0) was done using planter's built-in fertilizer delivery system.



Figure 3.1. Precision planter

Experimental design

The experiment utilized Unbalanced Randomized Complete block design. The experiments were conducted in two growing seasons 2024 and 2025. Each year two fields were planted with same treatments. Each field (Field A, Field B, Field C, Field D) was considered as an experimental block. In each block three planting depth treatments (38.1 mm, 50.8 mm and 63.5 mm) were applied with replications. Treatments were applied in such a way that during each pass of planter, row units 1-12 were assigned one depth treatment; row units 13-24 were applied with other depth treatment. After planting, in each of pass of planter we selected 8th row unit and 16th row unit to mark experimental strips of 5.33 meters for post planting data measurements. In each row unit, we marked twin strips. One of the strips were used for emergence, depth and spacing measurements; other was used to collect yield data.

Post Planting measurements

Emergence

Seedlings of marked strips were monitored twice a day in the mornings and the evenings in the gap of 12 hours consistently around 7 am and 7 pm. When the coleoptile was protruded above the soil surface and easily seen by naked eye without intervening the soil then seedlings were marked as emerged. All the strips were monitored within field until strips reached its complete emergence and no plants emerged further in all of the strips. During each visit emerged plants were marked using a wooden stake with length of 10cm and width of 1cm with

chronological code of particular date and time. From the day of first emergence, we recorded observations at 12-hour intervals, assigning consecutive numbers to each time point for every individual field (Figure 3.2). When complete emergence was obtained, plant numbers were designated to each of the plant in the strips to connect it to its corresponding depth, spacing and yield measurements.



Figure 3.2. Emergence measurements

Seeding depth

The Actual seeding depth of emerged plants was determined by excavating individual plants at the V4 stage. Seeding depth was defined as the vertical distance from the center bottom of the seed to the top of the soil surface. The measurement procedure followed a precise, multi-step protocol for each plant within the experimental units. First, a reference point was marked on the soil surface directly adjacent to the base of the plant stem, indicating the point of emergence without disturbing the surrounding soil. The plant was then carefully excavated to expose the entire root system and the buried seed, taking care not to damage the root structure. Finally, the vertical distance from the bottom of the seed to the previously marked soil surface reference point was measured using a measuring tape (Figure 3.3).



Figure 3.3. Depth measurement

Data analysis

The Data analysis was done using Python 3.11.5 in Jupiter Lab. The comprehensive analysis was done to evaluate the impact of different depth treatments on emergence uniformity in variable environmental conditions and its influence on yield. First the data preprocessing was done which included removal of outliers, interpolation of missing values in the dataset, manual formatting of data in excel. To evaluate the proper functioning of electronic depth control system, coefficient of variation of actual seed depth relative applied. Then Emergence uniformity was measured using logistics model which uses sigmoid function.

$$Y(t) = \frac{E_{\max}}{1 + e^{-(\beta_0 + \beta_1(t-t_{50})})} + \epsilon, \epsilon \sim N(0, \sigma^2)$$

Where, $y(t)$ = emergence at time t , $E_{\max}$ = asymptotic emergence, β_0 = intercept, β_1 = slope parameter, t_{50} = time to 50% emergence (DAE)

First the above model was done with emergence as the response variable modeled against days after the emergence (DAE) for complete dataset and then for each of the field. The time to 10%, 25%, 75%, 90% of emergence was then calculated for each of the field (T_{10} , T_{25} , T_{75} , T_{90}) to evaluate the emergence uniformity of each of field. Also, emergence window which is defined as the difference between the T_{90} and T_{10} was calculated for each field. Different models were explored and compared by adding more covariates such as soil temperature, precipitation, GDD. Yield response to variable depth treatment.

Result and Discussion

Achieved seed depth relative to target depth

In Field A (Kopfers), at 1.5 in target depth, the mean depth was 1.51 inch with mean CV of 8.53%. It indicated moderate variability among depth treatment within the field. At 2inch target depth, mean depth was 1.87 in which was slight shallower than the target but it was comparatively consistent as CV was 6.36%. At 2.5 in target, mean depth was 2.38in and CV was 11.52% which was both shallower and highly variable relative to other depth treatments in the field.

In Field B (TownsEnd), at 1.5 in target depth, the mean depth was 1.49 and mean CV was 9.91% which indicated variability relative to other treatments as the mean CV of 2in and 2.5in is low. Also, the depth treatment 2in had a mean depth 2in which indicated ideal working of E-depth system to achieve the target depth.

In Field C (Griffiths), the variability increased as the target depth increased from 1.5 in to 2.5 in. In Field C, all mean depth were shallower than target depth with a higher variation at deeper planting depth.

In Field D, mean depth of 1.5 in was closer target with less variability (CV =7.82%) relative to other depth treatment which had slightly higher variability (CV= 11.54 and 11.15%) with mean depth shallower than target depth (1.8 and 2.28in respectively).

Overall, achieved mean depth was close to target depths. There is slight variability in actual mean depth of different target depth within same field. These variations while planting all the fields with same operating speed might be due to different soil conditions and load distribution while selecting the margin which is the most influencing factor in depth variability. Based on the findings, it can be inferred that electronic depth control system was working efficiently to achieve the target depth.

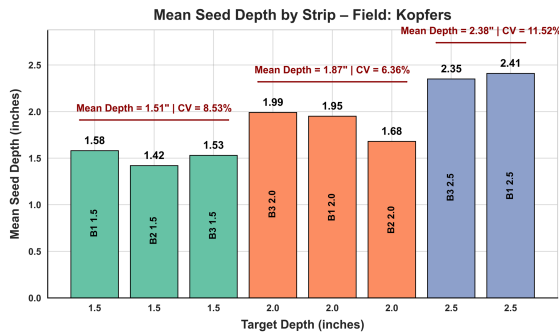


Figure 3.4. Field A Mean Seed Depth

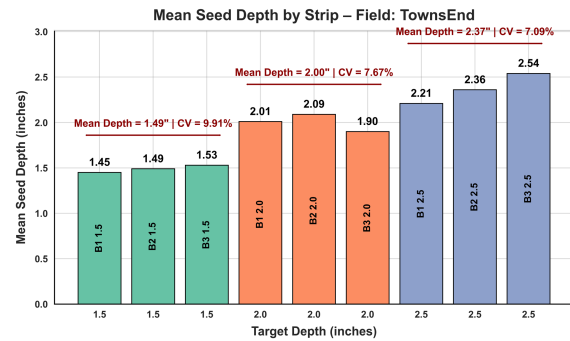


Figure 3.5. Field B Mean Seed Depth

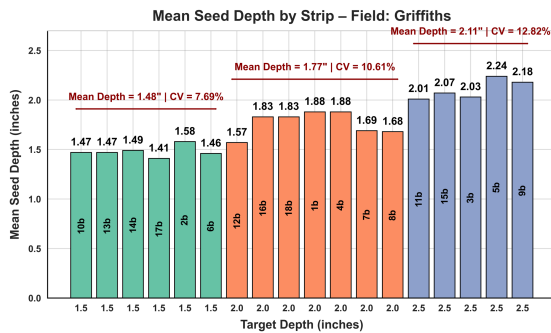


Figure 3.6. Field C Mean Seed Depth

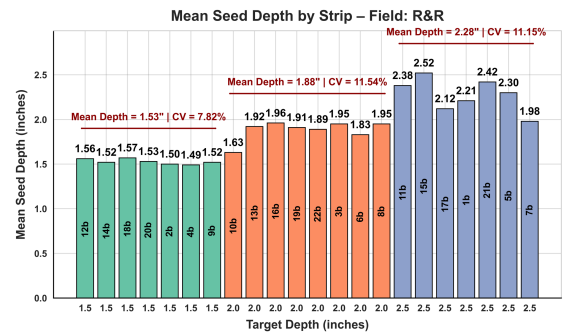


Figure 3.7. Field D Mean seed Depth

Live Plant Population

Before establishing the relationship between depth and emergence uniformity, live plant population was analyzed to assess potential stand losses caused by environmental or planting variations. Table 1 shows the live plant population of four fields. The Field A exhibited negligible to slightly negative losses (-3.12 to -0.33 %) that indicate that actual stands exceeded the target seeding rate of $23,000$ seeds ac^{-1} which might be due to slight overapplication of seeds while planting and favorable environmental & soil conditions that led to healthy stand. The live plant population of Field C varies from $26,923$ to $27,404$ plants ac^{-1} with a population loss of 2.13 – 3.85 % that indicate uniform and optimal stand establishment across depth treatments. Field D's live plant population dropped from $23,352$ plants ac^{-1} at 1.5 inches (2.7% loss) to $22,115$ plants ac^{-1} at 2.0 and 2.5 inches (7.85% loss) depths. At deeper placements, this suggests a decrease in emergence of uniformity. The greatest variability occurred in the Field B where stand losses increased sharply with depth from 9.19 % at 1.5 into 13.19% at 2.0 in and 21.21 % at 2.5 in. This trend suggests that deeper placement in heavier or drier soil conditions adversely affected stand establishment. Overall, these observations highlight that variations in achieved plant population

across fields were not only a result of depth treatment but also influenced by field-specific soil and environmental conditions. In order to achieve our desired plant population with respect to target seed rate, usually more seeds need to be put so that there won't be population loss relative to the desired target seed rate.

Table 3.1. Live plant population and population loss

Field	Depth (in)	Target Seed Rate (seeds/ac)	Live Plant Population (plants/ac)	Population Loss (%)
Field C (Griffiths)	1.5	28,000	27,083	3.27
	2.0	28,000	26,923	3.85
	2.5	28,000	27,404	2.13
Field A (Kopfers)	1.5	23000	23,718	-3.12
	2.0	23000	23,077	-0.33
	2.5	23000	23,077	-0.33
Field D R & R	1.5	24000	23,352	2.70
	2.0	24000	22,115	7.85
	2.5	24000	22,115	7.85
Field B Townsend	1.5	24000	21,795	9.19
	2.0	24000	20,833	13.19
	2.5	24000	18,910	21.21

Emergence dynamics with planting depth

Emergence dynamics were evaluated based on the actual number of plants observed in the field once no further emergence occurred. All calculations and evaluations in this study were performed with respect to the actual stand establishment rather than the theoretical population expected from the target seeding rate. This approach ensured that the emergence dynamics reflected true field performance and accounted for any deviations caused by environmental factors, soil conditions, or planter performance.

Emergence Uniformity with Time (DAE)

The fitted logistics curves indicated the differences in emergence dynamics across different target depth irrespective of varying field conditions. Emergence was fastest at 1.5 in target depth where

it reaches 50% of cumulative emergence approximately 1.9 days after the first emergence (DAE). Emergence was delayed to 2.5 DAE and 3.6 DAE for 2 inches and 2.5 inches depth respectively. Deeper seed depth led to prolonged time to emerge, and it reduced the stand count corresponding to its target seed rate. Cumulative emergence in figure 3.8 corresponds to percentage of plants emerged on the day. The results indicated that as target depth gets deeper corresponding final percentage of plants emerged decreased. Cumulative emergence was 87.6% at 1.5 in, 76.3% at 2 in and 46.4% at 2.5 in by the end of third day from the first emergence. Delayed emergence in deeper planted seeds might be due to plant physiology as deeper planted seeds require more energy to emerge out of soil due to increased soil resistance and reduced soil temperature buffering. Therefore, deeper seedlings either do not emerge due to unfavorable conditions to germinate or might emerge in opposite direction such that it is not visible on topsoil surface. Overall, shallower planting (1.5 inches) was most uniform with fastest emergence followed by 2 inches and 2.5 inches depth.

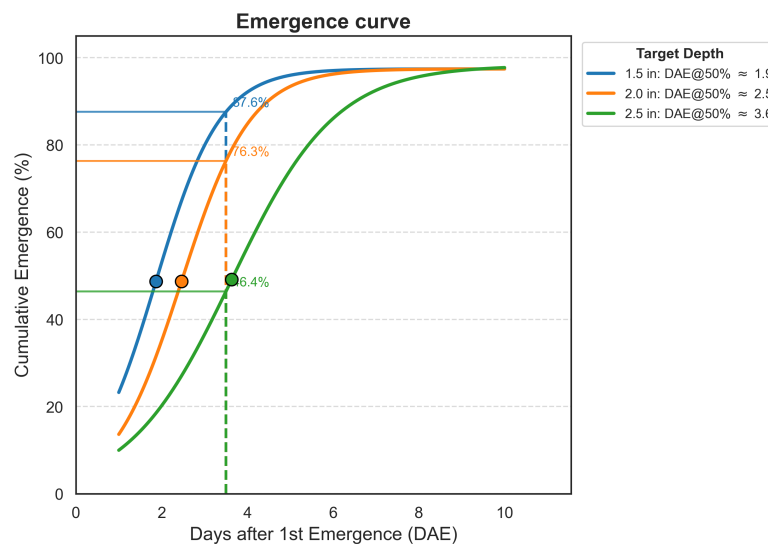


Figure 3.8. Overall emergence curve

In Field A, emergence dynamics varied substantially with planting depth (Figure 3.9). The logistic model indicated that shallower depths (1.5 and 2.0 in) promoted faster and more uniform emergence compared to the deeper (2.5 in) treatment. At 1.5 in, emergence progressed rapidly, reaching 13 % by Day 1, 36 % by Day 2, and 66 % by Day 3, with a midpoint (t_{50}) of 2.4 days after first emergence (DAE). Similarly, at 2.0 in, emergence reached 13 %, 41 %, and 73 % by Days 1, 2, and 3, respectively, with a slightly earlier t_{50} of 2.1 DAE. In contrast, the 2.5 in depth exhibited markedly delayed emergence, attaining only 3 %, 5 %, and 8 % by Days 1, 2, and 3,

respectively, with a t_{50} of 11.2 DAE. Time-to-event analysis (**Table 2**) further supported these observations. At 1.5 in, 10 % emergence occurred within 0.73 days, and 90 % by 4.11 days, resulting in a $T_{90}-T_{10}$ interval of 3.38 days. The 2.0-in treatment showed a similar pattern with a narrow 2.66-day window, whereas the 2.5-in depth extended the interval to 8.18 days, reflecting delayed and less synchronized emergence. Overall, these results demonstrate that shallower seed placements (1.5–2.0 in) promoted rapid and uniform emergence, while deeper placement (2.5 in) substantially slowed emergence and increased variability. Although deeper seeding may be advantageous under dry conditions to access moisture, it comes at the cost of slower and less uniform seedling establishment.

In Field B, emergence patterns varied notably with increasing seeding depth (Figure 3.10). The logistic model revealed that the shallowest depth (1.5 in) exhibited the most rapid and uniform emergence, achieving 40 % by Day 1, 71 % by Day 2, and 90 % by Day 3, with a midpoint (t_{50}) of 1.3 days after first emergence (DAE). At 2.0 in, emergence was slower, reaching only 19 % by Day 1, 40 % by Day 2, and 66 % by Day 3, with a t_{50} of 2.4 DAE, while the 2.5 in treatment showed the greatest delay, with 4 %, 13 %, and 31 % emergence by Days 1, 2, and 3, respectively, and a t_{50} of 3.8 DAE. The time-to-event indices further confirmed these trends: at 1.5 in, 10 % emergence occurred within 0.38 days, and 90 % by 2.96 days, resulting in a $T_{90}-T_{10}$ interval of 2.58 days. Deeper depths (2.0 in and 2.5 in) exhibited wider emergence windows of 4.19 and 3.94 days, respectively, indicating greater variability among seedlings. Overall, the 1.5-inch depth produced the fastest and most synchronized seedling establishment, while deeper placements delayed emergence and reduced uniformity.

In Field C (Griffiths) emergence trend was the opposite of what was seen for other fields. Deeper planting depths (2.0 and 2.5 in) was faster and uniform than shallower (1.5 in). With a midpoint (t_{50}) of 1.8 days after first emergence (DAE), emergence at 1.5 inches reached 32% by Day 1, 52% by Day 2 and 70% by Day 3. By contrast, the 2.0-in depth reached 21%, 52%, and 81% emergence by Days 1, 2, and 3, respectively, with a t_{50} of 1.9 DAE, whereas the 2.5-in depth reached 17%, 46%, and 76% over the same period with a t_{50} of 2.1 DAE.

The emergence window ($T_{90}-T_{10}$) was also narrower at deeper depth 3.04 days at 2.0 inches and 3.12 days at 2.5 inches compared with 4.10 days at the shallowest depth that indicates greater synchrony among seedlings at the deeper treatments. This deviation from the general trend suggests that field-specific conditions influenced emergence behavior. It is likely that at the 1.5-in

target depth, ineffective residue management or improper row-cleaner performance left excessive residue or uneven soil coverage that hindered seed–soil contact and delaying emergence. These findings underscore that localized field and equipment factors can override general depth recommendations, emphasizing the importance of proper planter setup and residue management along with depth selection to achieve rapid and uniform emergence.

In Field D, emergence patterns followed a trend like other fields, where shallower seeding depths supported faster and more uniform emergence. At the 1.5-in depth, emergence progressed rapidly, reaching 15 % by Day 1, 54 % by Day 2, and 88 % by Day 3, with a midpoint (t_{50}) of 1.9 days after first emergence (DAE). In comparison, the 2.0-in treatment showed slower progress with 3 %, 15 %, and 47 % emergence by Days 1, 2, and 3, respectively, and a t_{50} of 3.0 DAE, while the 2.5-in depth exhibited the greatest delay, achieving only 5 %, 13 %, and 29 % over the same interval, with a t_{50} of 3.8 DAE. Time-to-event analysis further confirmed the advantage of shallower placement. At 1.5 in, 10 % emergence occurred within 0.74 days and 90 % by 3.63 days, resulting in a narrow T_{90} – T_{10} interval of 2.31 days, indicating strong emergence uniformity. In contrast, deeper depths widened the emergence window to 2.7 days (2.0 in) and 4.9 days (2.5 in), reflecting slower and less synchronized emergence. From an agronomic standpoint, these results reinforce that shallower seeding (around 1.5 in) consistently promotes faster and more uniform emergence. The gradual decline in uniformity with increasing depth suggests that deeper placements introduce variability that may reduce early stand establishment and yield potential. Overall, the findings emphasize the importance of precise planter depth control to maintain consistent emergence under varying field and soil conditions.

With shorter emergence windows (T_{90} – T_{10}) and higher cumulative emergence than deeper placements, the 1.5 in depth consistently produced the fastest and most uniform emergence across Field A, Field B, Field D. On the other hand, 2.5 in reduced uniformity by delaying emergence by a few days and expanding the emergence window. The exception was the Field C, where 1.5 in depth was inferior to 2.0–2.5 in. This was likely caused by issues with residue management or planters that reduced seed-to-soil contact in the shallowest setting. A planting depth of between 1.5 and 2.0 inches is usually ideal for rapid and reliable stand establishment, where deeper planting should be avoided unless the soil moisture conditions. Effective planter setup and residue management are crucial to ensuring that these advantages are experienced in all fields.

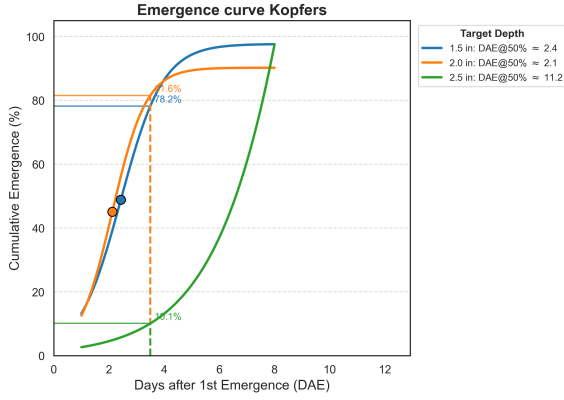


Figure 3.9. Field A Emergence curve

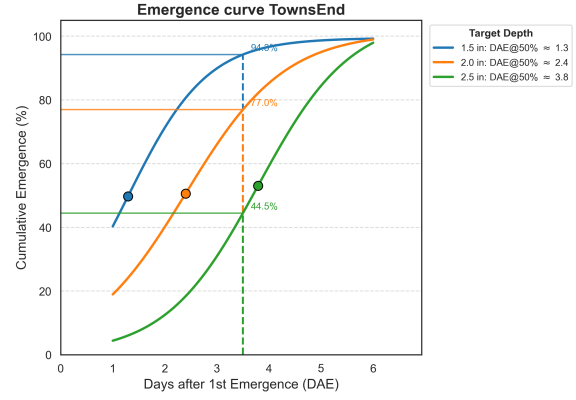


Figure 3.10. Field B Emergence curve

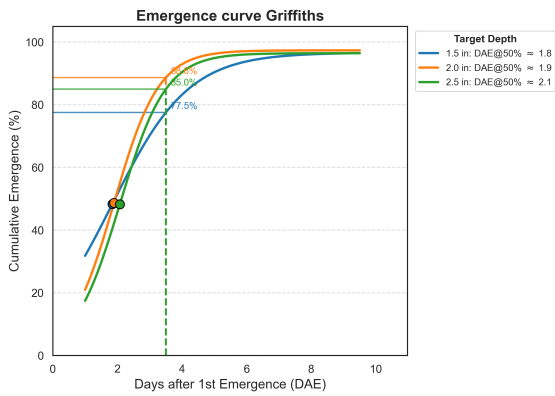


Figure 3.11. Field C Emergence curve

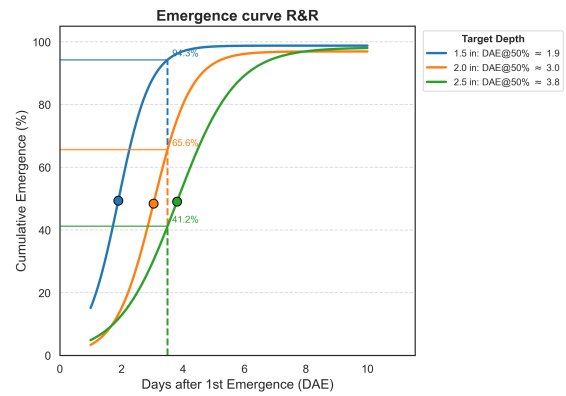


Figure 3.12. Field C Emergence curve

Table 3.2. Time to event emergence indices

Field	Target Depth	T10	T25	T75	T90	T 95	T90-T10
Kopfers	1.5	0.73	1.58	3.27	4.11	4.69	3.38
	2.0	0.79	1.45	2.78	3.45	3.90	2.66
	2.5	7.09	9.13	13.22	15.27	16.66	8.18
TownsEnd	1.5	0.38	0.45	2.12	2.96	3.5	2.58
	2.0	0.30	1.35	3.44	4.49	5.20	4.19
	2.5	1.8	2.81	4.76	5.74	6.41	4.94
Griffiths	1.5	0.34	0.54	3.14	4.44	5.32	4.1
	2.0	0.37	1.3	2.65	3.41	3.92	3.04

	2.5	0.51	1.29	2.85	3.63	4.16	3.12
R&R	1.5	0.74	1.32	2.47	3.05	3.45	2.31
	2.0	1.69	2.36	3.72	4.39	4.85	2.7
	2.5	1.71	2.76	4.85	5.90	6.61	4.19

Weather conditions during planting differed substantially between years. According to Kansas Mesonet records (2025), total precipitation during the 15 days before planting and after 15 days in 2024 was 46.99 mm and in 2025 it was 101.854 mm. The cooler and wetter post-planting period contributed to slower early emergence across all depth settings in 2024, due to emergence window for Field A and Field B was longer than Field C and Field D in 2025. Average soil moisture content for Field A was 24.7%, Field B was 27.4%, Field C was 30.9 % and Field D was 31%.

Emergence Uniformity with Covariates

Across all four fields (Kopfers, TownsEnd, Griffiths, and R&R), a consistent trend was observed in which shallower planting depths led to faster and more uniform corn emergence due to a narrower emergence window which was consistent with past research (Alessi & Power, 1971; Gupta et al., 1988). However, the specific timing to reach comparable emergence percentages varied among fields, reflecting differences in microclimate, soil texture, and moisture conditions (Ford & Hicks, 1992). These results suggest that emergence uniformity is not solely time-dependent but is influenced by multiple interacting covariates such as soil temperature, soil structure, and field-specific characteristics.

To better understand these relationships, a logistic model was fitted incorporating soil temperature, GDD and precipitation as covariates along with days after emergence (DAE) (Schneider & Gupta, 1985; Cutforth et al., 1986). Three-dimensional surface plots were generated to visualize the interaction between soil temperature and DAE on cumulative emergence for each field and planting depth.

Field A (Kopfers)

At Kopfers, emergence dynamics showed a clear depth-dependent response. At the 1.5-inch depth (Figure 3.13), cumulative emergence increased rapidly within the first 3-4 DAE,

reaching almost 80% once soil temperatures remained above 62 °F. The steep surface gradient reflected highly synchronized emergence, indicating that warmer soil conditions favored rapid germination and early growth (Cutforth et al., 1986). Increasing planting depth to 2.0 inches slowed the emergence rate and extended the emergence window to 4–5 days, with maximum emergence reaching around 70–80%. This suggests that deeper placement increased soil resistance and reduced oxygen diffusion near the seed (Gupta et al., 1988). At 2.5 inches, emergence was further delayed and less uniform, with a flatter surface indicating a slow progression toward the 70–75% plateau. This depth dependency in Kopfers highlights how excessive planting depth can limit early stand establishment, particularly under cooler soil conditions (Alessi & Power, 1971).

Field B (TownsEnd)

A similar pattern was observed at TownsEnd, though emergence occurred slightly earlier overall, likely due to warmer soil profiles (Ford & Hicks, 1992). At 1.5 inches emergence was rapid and uniform, reaching near 85% within 3–4 DAE when soil temperatures exceeded 63 °F (Cutforth et al., 1986). The 2.0-inch treatment showed a moderate delay, requiring 4–5 days to reach 70–80% emergence, while the 2.5-inch depth extended the emergence period to nearly 6 days, with final emergence declining to 75–80%. The smoother curvature at deeper depths indicates reduced synchrony, driven by increased elongation distance and lower thermal conductivity in the deeper seed zone (Schneider & Gupta, 1985). These observations reaffirm that shallow planting under adequate thermal and moisture conditions promotes uniform emergence and vigorous early growth (Nafziger, 1994).

Field C (Griffiths)

In the Griffiths field, the logistic model captured a well-defined sigmoidal emergence response across all depths. At 1.5 inches, emergence exceeded 70% within 4 DAE when soil temperatures were around 58–60 °F, while cooler conditions (56–57 °F) delayed emergence to 6–7 DAE (Cutforth et al., 1986). The pattern was similar at 2.0 inches but with slightly slower progression such that emergence reached 70% by 4–5 DAE under warm conditions and was slightly delayed under cooler soils. At 2.5 inches, emergence was consistently the fast and uniform as steep slope of surface relative to other treatments in Field Griffiths. Collectively, Griffiths data

demonstrated that soil temperature was the dominant factor governing emergence timing but due to inappropriate working of row cleaner during this experimental unit 1.5 inches had not exhibit fast and uniform emergence. Also, at shallower depth cooler temperature delayed emergence is also a result of ongoing precipitation around the planting days of Field C. Field C had wetter conditions compared to other fields.

Field D (R&R)

Emergence trends at R&R followed the same general relationship but slightly delayed response due to cooler average soil temperatures (Ford & Hicks, 1992). The 1.5-inch depth achieved rapid and synchronized emergence, with more than 80% of seedlings emerging within 3–4 DAE when temperatures were between 58 and 60 °F. At 2.0 inches emergence remained fairly uniform but was delayed by roughly one day, reaching 85–90% final emergence. The 2.5-inch depth showed a slower cumulative response that required 6–8 days to stabilize near 75–80% emergence. This delay reflects the combined effects of cooler soil and increased penetration resistance at greater depths (Gupta et al., 1988).

Across all sites, the 3D surface models clearly demonstrated that both soil temperature and planting depth strongly influence the rate and uniformity of corn emergence (Schneider & Gupta, 1985; Cutforth et al., 1986). Shallower placements (1.5 inches) consistently promoted faster and more complete emergence due to improved soil warmth, oxygen diffusion, and reduced resistance to coleoptile elongation (Alessi & Power, 1971). Deeper placements (2.0–2.5 inches) delayed emergence and widened the emergence window, reducing stand uniformity (Gupta et al., 1988). These findings highlight the importance of optimizing planting depth according to field-specific thermal and structural conditions. While 2.0 inches remains within agronomic recommendations, the results emphasize that depth–temperature interactions should guide depth adjustments to ensure uniform seedling emergence, which is critical for achieving consistent stand establishment and maximizing yield potential (Liu et al., 2004; Nafziger, 1994)

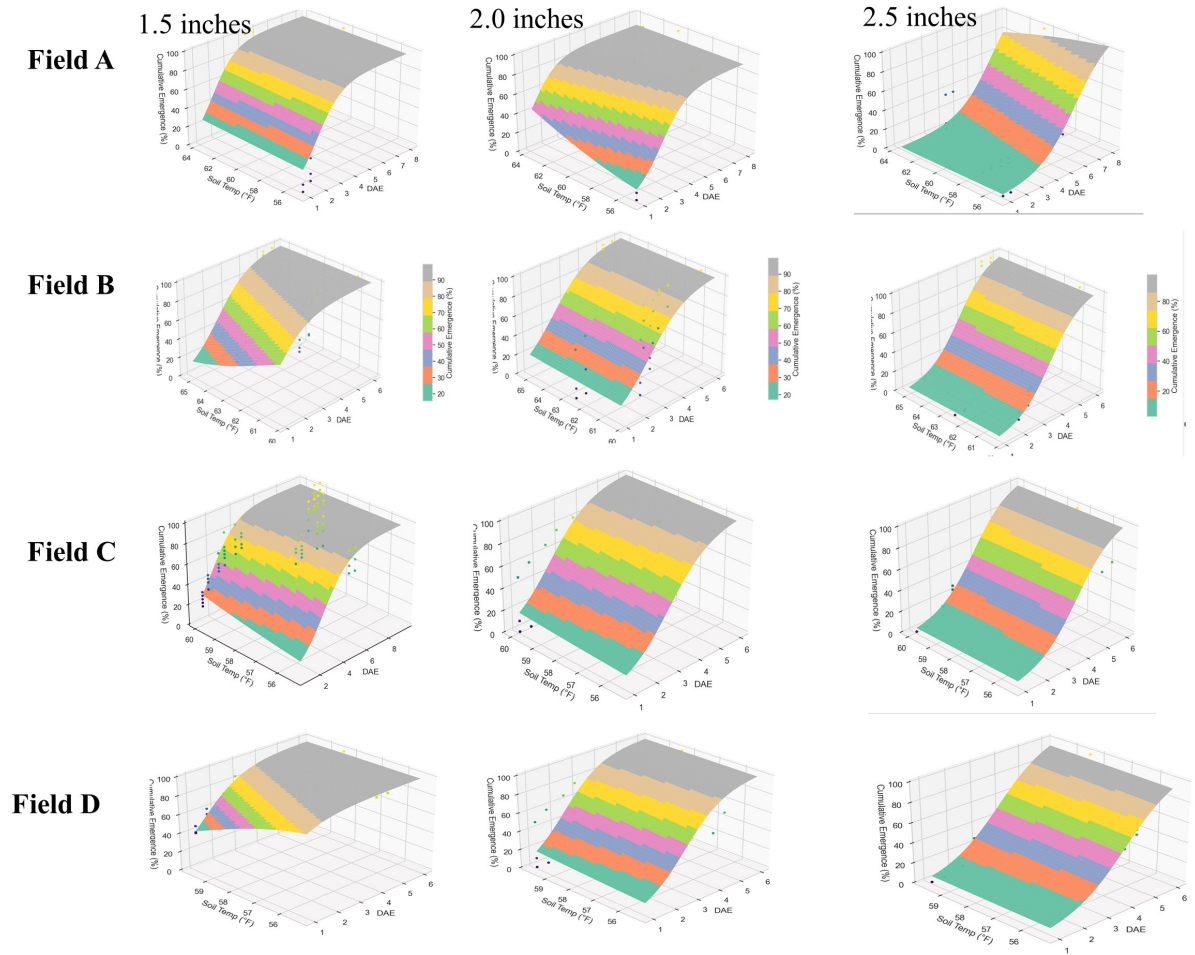


Figure 3.13. Surface graph for emergence with soil temperature and DAE

Emergence with GDD

1.5-Inch Planting Depth

For the 1.5-inch planting depth, the time to 95 % emergence ranged from 3.5 to 5.32 days across the four fields, corresponding to accumulated GDDs of 122.75 to 159.71 (Table 3.3). Field D exhibited the fastest emergence (3.4 days, 122.75 GDD) and the narrowest emergence window (2.31 days), indicating highly synchronous emergence likely driven by optimal soil temperature and moisture conditions. In contrast, Field C showed the slowest emergence (5.32 days, 159.71 GDD) and the widest emergence window (4.19 days), suggesting suboptimal soil properties such as compaction or reduced thermal conductivity that delayed seedling development (Schneider & Gupta, 1985). The moderate GDD variability across fields (36.96 GDD) and the relatively narrow range of emergence times indicate generally consistent thermal conditions at this depth, with field-specific factors influencing emergence dynamics.

2.0-Inch Planting Depth

At the 2.0-inch planting depth, the time to 95 % emergence ranged from 3.9 to 5.20 days, corresponding to accumulated GDDs of 143.42 to 176.90. Field A exhibited the fastest emergence (3.9 days, 145.96 GDD), whereas Field B had the slowest emergence (5.2 days, 176.90 GDD) and the widest emergence window (4.19 days). In contrast, Field D showed the narrowest emergence window (2.66 days), reflecting favorable conditions for uniform emergence. The GDD variability across fields was 33.48 GDD that was slightly lower than at the 1.5-inch depth indicating moderate differences in thermal time requirements among fields. Field B's higher GDD and prolonged emergence period suggest slower heat accumulation, likely due to cooler or more heterogeneous moisture conditions in deeper soil layers. Conversely, the narrower emergence window in Field D highlights the role of favorable thermal and moisture regimes in promoting rapid, synchronized emergence, consistent with previous findings that shallower depths facilitate quicker seedling establishment under optimal conditions.

2.5-Inch Planting Depth

At the 2.5-inch planting depth, emergence timing was highly variable, with 95 % emergence ranging from 4.16 to 16.66 days and accumulated GDDs from 150.33 to 250. Field C exhibited the fastest emergence (4.16 days, 150.33 GDD), whereas Field A showed a pronounced delay (16 days, 250 GDD). The substantial GDD variability (99.67 GDD) indicates considerable differences in thermal time requirements among fields. Although detailed emergence windows were not reported, similar variability is expected based on the emergence trends. The pronounced delay in Field A suggests that deeper planting amplified the influence of field-specific factors such as soil texture, moisture distribution, and temperature gradients on heat accumulation and seedling vigor. These findings align with previous research showing that deeper sowing increases the thermal time required for seedlings to emerge (Mahdi et al., 1998), highlighting the greater sensitivity of deeper-planted crops to spatial heterogeneity in soil and environmental conditions.

Table 3.3. Emergence and GDD

Planting Depth	Field	Time to 95% Emergence (days)	Accumulated GDD	Emergence Window (days)
---------------------------	--------------	---	----------------------------	--

1.5 inches	Field A Kopfers	4.69	156.38	3.38
	Field B3.5		144.4	2.58
	TownsEnd			
	Field C Griffiths	5.32	159.71	4.19
	Field D R&R	3.45	122.75	2.31
2.0 inches	Field A Kopfers	3.9	145.96	2.66
	Field B5.20		176.90	4.19
	TownsEnd			
	Field C Griffiths	3.92	150.33	3.04
	Field D R&R	4.85	143.42	2.7
2.5 inches	Field A Kopfers	16.66	250	8.18
	Field B6.41		176.90	3.94
	TownsEnd			
	Field C Griffiths	4.16	150.33	3.12
	Field D R&R	6.61	156.69	4.19

Yield

Yield response to planting depth

Initially the objective was to analyze the response of different target depth treatment on yield which was done for both of year which stated that Yield was not significantly impacted by target planting depth in any of the fields ($p > 0.05$). Despite a slight variation in mean yields, the differences were not statistically significant and were inconsistent (Table 3.4). While yields in Kopfers, R & R, and TownsEnd were consistent across 1.5–2.5 in depths, yields in Griffiths were slightly higher at 1.5 in ($15.6\text{--}16.9\text{ t ha}^{-1}$). Furthermore, the overlapping confidence intervals show that yield results were unaffected by depth variation within this range. Overall, these results imply that although planting depth influences emergence dynamics, it had little direct effect on final grain yield, suggesting that management and environmental factors were probably more important in determining yield.

Field	F-value	p-value	95% Confidence Interval for Mean Yield (t ha^{-1})
Griffiths	2.01	0.168	1.5 in: 15.6–16.9; 2.0 in: 14.5–15.9; 2.5 in: 14.0–16.5
Kopfers	0.36	0.714	1.5 in: 10.1–15.1; 2.0 in: –0.03–19.9; 2.5 in: 6.4–16.9

R & R	0.18	0.834	1.5 in: 9.0–10.3; 2.0 in: 9.1–10.9; 2.5 in: 9.2–10.6
TownsEnd	0.05	0.950	1.5 in: 4.6–11.5; 2.0 in: 2.8–13.5; 2.5 in: 7.0–8.2

Yield response to interaction of planting depth and Emergence

In 2024, results indicated that depth does not have significant impact on yield response. Therefore, next year (2025) yield data was collected in response to emergence status and combined effect of emergence and depth were analyzed. The impact of target planting depth and emergence status on corn yield at the Griffiths field was investigated using a two-way ANOVA (Table 3.4). The findings showed that target depth ($p = 0.137$) did not have main effect on yield and emergence status ($p = 0.00012$) significantly impacted yield. Furthermore, emergence status and planting depth had a significant interaction effect ($p = 0.0026$), suggesting that the impact of emergence timing on yield differed depending on the depth treatment. In comparison to late and mid-emerged plants, early emerged plants typically produced higher and more consistent yields across all depth treatments, as shown in the boxplot (Figure 3.14). While yields among early emergers were more variable and showed a wider interquartile range at 2.5 inch, they were comparatively uniform and clustered around 17–18 t ha⁻¹ at the 1.5 inch and 2.0-inch target depths. Conversely, plants that emerged later showed both a lower median yield and greater variability, particularly at the deeper (2.5 inch) depth. This suggests that stand performance may be inconsistent and that delayed emergence may result in penalties.

Timely emergence is a critical factor in determining yield potential, as evidenced by the notable main effect of emergence status. Greater biomass accumulation and kernel set were probably the results of early-emerging plants gaining a competitive edge in light interception, nutrient uptake, and root development. This is consistent with previous studies that demonstrate that plants that emerge later than the main cohort frequently contribute disproportionately less to total yield because of reduced photosynthetic capacity and delayed growth stages (Nafziger et al., 1991; Liu et al., 2004).

The impact of target planting depth lends more credence to the idea that depth affects yield results. Maintaining adequate seed-to-soil contact and moisture availability favors rapid and uniform emergence, according to the optimal yield performance seen at intermediate depth (2.0 inches). The thermal and moisture conditions of the soil surrounding the seed were probably

changed by shallower or deeper placements, which slowed germination and decreased homogeneity. The substantial interplay between depth and emergence status suggests that planting depth has an impact on emergence timing. In particular, the yield penalty linked to delayed emergence increased with deeper placement (2.5 in). This implies that when planting depth deviates from ideal conditions, the detrimental effects of non-uniform emergence are exacerbated possibly as a result of greater variability in soil temperature and oxygen diffusion in the seed zone.

Overall, these results emphasize that maintaining uniform emergence within the optimal depth range (approximately 2.0 in) is key to achieving stable and high yields under the Griffiths field conditions. Adoption of precise electronic depth control and appropriate gauge wheel load management can help minimize emergence variability and improve yield consistency across field environments.

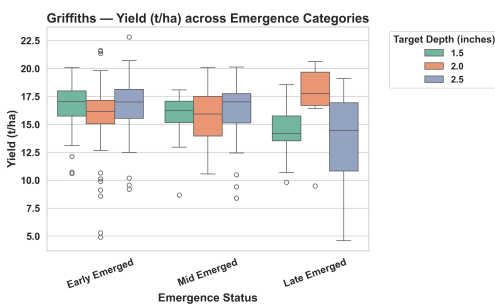


Figure 3.14. Yield response to emergence and depth- Griffiths

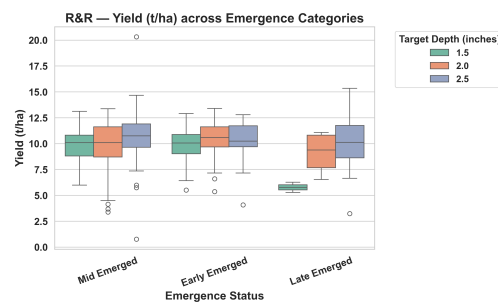


Figure 3.15. Yield response to emergence and depth- R&R

The two-way ANOVA indicated similar trends such that emergence status ($p = 0.0086$) had significant effect whereas target planting depth ($p = 0.244$) had no significant effects on yield at the R&R field, while their interaction was also significant ($p = 0.036$). These results suggest that yield response varied with both emergence timing and depth, and that the influence of emergence timing depended on the target planting depth.

The boxplot (Figure 3.15) shows that yield variability across emergence categories was smaller than that observed at the Griffiths field, yet consistent trends were evident. Early- and mid-emerged plants generally yielded higher than late-emerged ones, particularly at deeper planting depths (2.0 and 2.5 inches). At the shallowest depth (1.5 in), late emergence resulted in the greatest yield reduction, with median yield dropping below 6 t ha^{-1} . In contrast, the 2.0-inch and 2.5-inch

treatments displayed more stable yield distributions, with higher medians (10–12 t ha⁻¹) and fewer extreme outliers.

The main effects of emergence status and planting depth highlight that emergence uniformity strongly influenced yield outcomes under the R&R field conditions. Early and synchronized emergence allowed plants to achieve better stand establishment and light interception, promoting higher grain yield. This observation aligns with the findings of Nafziger et al. (1991) who reported that early-emerged plants in corn maintain competitive dominance and contribute disproportionately to total yield, whereas late-emerged plants experience reduced kernel set and grain filling efficiency.

The significant interaction indicates that optimal seed placement with early emergers remains a key factor in achieving consistent emergence and yield. Deeper seed placement (2.0–2.5 in) appeared to mitigate the negative effects of late emergence, possibly due to improved seed-soil moisture contact and temperature buffering in R&R’s coarser soil texture. Similar findings have been reported by Badua et al. (2021), who noted that moderate depths promote uniform soil moisture conditions and enhance planter performance stability. The significant interaction effect between emergence status and planting depth ($p = 0.036$) further demonstrates that the benefits of uniform emergence are modulated by the achieved planting depth. At shallower depths, yield losses from delayed emergence were magnified likely due to uneven soil moisture and temperature fluctuations that hinder germination uniformity. Conversely, at optimal or slightly deeper depths, yield differences among emergence categories were less pronounced, indicating more resilient stand establishment.

Overall, the R&R field results confirm that both uniform emergence and appropriate planting depth (2.0 inches) are essential for maximizing yield stability. These findings emphasize the need for precise depth regulation systems and real-time downforce control to ensure consistent emergence across variable field conditions.

Table 3.4. ANOVA for emergence and depth interaction

Field	Source of Variation	df	F-value	p-value
Griffiths	Emergence Status	2	9.16	0.00012

	Depth Treatment	2	6.08	0.137
	Emergence Status × Depth Treatment (Interaction)	4	4.23	0.00226
R & R	Emergence Status	2	4.80	0.00860
	Depth Treatment	2	1.41	0.24433
	Emergence Status × Depth Treatment (Interaction)	4	2.59	0.03628

Conclusion

This study showed that corn emergence dynamics and yield performance are significantly impacted by planting depth. Because seeds required ideal thermal conditions and less soil mechanical resistance, shallower placements (about 1.5 inches) continuously encouraged quicker and more consistent seedling emergence across several fields. Conversely, deeper placements (2.0–2.5 inches) needed more accumulated growing degree days (GDD) to reach emergence, which frequently led to less coordinated and delayed stand establishment, especially in cooler or more heterogeneous soil conditions.

Variability in actual seed placement within and between fields reflected variations in soil texture, moisture, and gauge wheel load margins, even though the electronic depth control (eDepth) system kept depths near their targets. In order to attain uniform depth and ideal emergence, these results highlight the significance of accurate planter calibration, appropriate downforce settings, and flexible field management. Differences at the field level also demonstrated that interactions between soil temperature, planting depth, and structural conditions, rather than just time, control emergence uniformity. Temperature and depth interactions are a key factor in determining emergence rate and uniformity, according to logistic modeling and surface response analyses. Deviations from expected patterns are frequently linked to residue distribution or planter performance in variable field conditions. Field level differences in emergence are also derived from variability in moisture as average precipitation of experimental years was 101.854mm a d 46.99 mm which was highest average of the same time period from last 5 years.

Yield was greatly impacted emergence status, with significant interaction effects with planting depth. While delayed emergence resulted in quantifiable yield penalties, particularly at suboptimal depths, early emerged plants consistently produced higher yields across all fields. With consistent yields across emergence categories, the intermediate depth of 2.0 inches turned out to be the most advantageous. On the other hand, planting too deeply (2.5 inches) decreased yield potential and increased variability, especially in cases of delayed emergence.

Overall, planting depths between 1.5 and 2.0 inches provided the best balance between rapid emergence, uniform stand establishment, and yield stability. These results emphasize that optimal depth selection must be field-specific, accounting for soil thermal and structural conditions rather than relying solely on generalized recommendations. Effective use of electronic depth control systems, when coupled with appropriate residue management and gauge wheel load margin adjustments can significantly improve planting depth accuracy, enhance emergence uniformity, and support consistent yield outcomes under variable soil and environmental conditions.

Chapter 4 - Conclusion

The purpose of this research was to develop a data-driven understanding of depth management that supports farmers in achieving optimal and consistent seeding depth under variable field conditions. By coupling planter mechanics with agronomic parameters, the study connects engineering performance with crop responses related to emergence uniformity, stand establishment, and yield potential.

Maintaining a consistent gauge wheel load (GWL) margin proved vital for achieving accurate seeding depth, stable planter operation, and uniform crop emergence across different soil and terrain conditions. Statistical analysis revealed that seeding depth, planter speed, and acceleration significantly influenced GWL stability, with seed depth being the most dominant factor. Optimal performance occurred when GWL margins were maintained between 778–1112 N, resulting in lower depth variability, improved soil contact, and smoother ride quality. As planting speed increased, lighter margins failed to maintain consistent soil contact, while higher margins sustained stable loads and uniform seed placement. GWL distribution also varied across planter sections, with wing rows showing higher variability than track rows due to differences in surface compaction. These findings emphasize that managing speed, downforce, and section-specific GWL settings is essential to enhance depth consistency, promote uniform emergence, and enable data-driven planting decisions for improved stand establishment and yield stability.

The research also identified a notable influence of planting depth on corn emergence dynamics and yield outcomes. Shallower depths around 1.5 inches generally resulted in faster and more uniform emergence due to favorable thermal and mechanical conditions compared with deeper placements (2.0–2.5 inches), which required greater growing degree days (GDD) and often produced delayed or uneven stands under cooler or heterogeneous soils. Although the electronic-depth (E-Depth) control system-maintained depths near targets, variability in soil texture, moisture, and GWL margin still affected emergence uniformity. Yield was strongly linked to emergence timing, with early-emerged plants consistently producing higher yields than late emergers across all treatments. The 2.0-inch depth provided the best balance between rapid emergence, uniform stand establishment, and yield consistency.

Overall, the findings demonstrate that optimal planting depth is achievable when planters are properly calibrated and operated with well-managed downforce, GWL margin, and residue

conditions. Integrating these mechanical and agronomic insights offers a path toward precision, data-driven planting systems capable of improving seeding depth accuracy, emergence uniformity, and yield stability across variable field environments.

References

- Alessi, J., Power, J. F. (1971). Corn Emergence in Relation to Soil Temperature and Seeding Depth¹. *Agronomy Journal*, 63(5), 717–719.
<https://doi.org/10.2134/agronj1971.00021962006300050018x>
- Alm, D. M., Stoller, E. W., Wax, L. M. (1993). An Index Model for Predicting Seed Germination and Emergence Rates. *Weed Technology*, 7(3), 560–569.
<https://doi.org/10.1017/S0890037X00037349>
- Badua, Sylvester Alfredo. (2008). Control system response for seed placement accuracy on row crop planters.
- Badua, S. A., Sharda, A., Strasser, R., Ciampitti, I. (2021). Ground speed and planter downforce influence on corn seed spacing and depth. *Precision Agriculture*, 22(4), 1154–1170.
<https://doi.org/10.1007/s11119-020-09775-7>
- Badua, S., Sharda, A., Flippo, D. (2019). Sensing System for Real-Time Measurement of Seed Spacing, Depth, and Geo-Location of Corn: A Proof-of-Concept Study. *Transactions of the ASABE*, 62(6), 1779–1788. <https://doi.org/10.13031/trans.13593>
- Badua, Sylvester A., Sharda, A., Aryal, B. (2024). Quantifying real-time opening disk load during planting operations to assess compaction and potential for planter control. *Precision Agriculture*, 25(4), 2020–2032. <https://doi.org/10.1007/s11119-024-10151-y>
- Badua, Sylvester A., Sharda, A., Flippo, D., Ciampitti, I. A. (2018). Real-Time Gauge Wheel Load Variability of a Row-Crop Planter During Field Operation. *Transactions of the ASABE*, 61(5), 1517–1527. <https://doi.org/10.13031/trans.12511>
- Blacklow, W. M. (1972). Influence of Temperature on Germination and Elongation of the Radicle and Shoot of Corn (*Zea mays* L.)¹. *Crop Science*, 12(5), 647–650.
<https://doi.org/10.2135/cropsci1972.0011183X001200050028x>

- Brady, N. C., & Weil, R. R. (2002). The nature and properties of soils. Prentice Hall
- Carter, P. R., Nafziger, E. D., & Lauer, J. G. (1989). Uneven emergence in corn. Urbana-Champaign: University of Illinois at Urbana-Champaign: Cooperation Extension Service for North Central Regional Extension Service.
- Cox, W. J., Cherney, J. H. (2015). Field-Scale Studies Show Site-Specific Corn Population and Yield Responses to Seeding Depths. *Agronomy Journal*, 107(6), 2475–2481.
<https://doi.org/10.2134/agronj15.0308>
- Cutforth, H. W., Shaykewich, C. F., Cho, C. M. (1986). EFFECT OF SOIL WATER AND TEMPERATURE ON CORN (*Zea mays* L.) ROOT GROWTH DURING EMERGENCE. *Canadian Journal of Soil Science*, 66(1), 51–58. <https://doi.org/10.4141/cjss86-006>
- D. Karayel, A. Özmerzi. (2008). Evaluation of Three Depth-Control Components on Seed Placement Accuracy and Emergence for a Precision Planter. *Applied Engineering in Agriculture*, 24(3), 271–276. <https://doi.org/10.13031/2013.24494>
- Dam, R. F., Mehdi, B. B., Burgess, M. S. E., Madramootoo, C. A., Mehuys, G. R., Callum, I. R. (2005). Soil bulk density and crop yield under eleven consecutive years of corn with different tillage and residue practices in a sandy loam soil in central Canada. *Soil and Tillage Research*, 84(1), 41–53. <https://doi.org/10.1016/j.still.2004.08.006>
- Dufour, J., Dufour, J. M. (2021). Effects of Plant Spacing Variability and Non-Uniform Emergence Effects of Plant Spacing Variability and Non-Uniform Emergence on Corn Yield. Retrieved from https://digitalcommons.lsu.edu/gradschool_theses
- Hoelt, R. G., Nafziger, E. D., Johnson, R. R., & Aldrich, S. R. (2000). Modern corn and soybean production. MCSP Publications.
- Kansas Corn Management (2025). Retrieved from <https://eupdate.agronomy.ksu.edu/>
- Kansas State University Research and Extension. 2019. Corn Production Handbook (C560). Manhattan, KS: Kansas State University Agricultural Experiment Station and Cooperative Extension Service.

- Dwyer, L. M., Ma, B. L., Jong, R. D., Tollenaar, M. (2000). Assessing corn seedbed conditions for emergence. *Canadian Journal of Soil Science*, 80(1), 53–61. <https://doi.org/10.4141/S99-003>
- Elmer B. Hudspeth, Jr. And Donald F. Wanjura. (1970a). A Planter for Precision Depth and Placement of Cottonseed. *Transactions of the ASAE*, 13(2), 0153–0154.
<https://doi.org/10.13031/2013.38558>
- Forcella, F., Benech Arnold, R. L., Sanchez, R., Ghersa, C. M. (2000). Modeling seedling emergence. *Field Crops Research*, 67(2), 123–139. [https://doi.org/10.1016/S0378-4290\(00\)00088-5](https://doi.org/10.1016/S0378-4290(00)00088-5)
- Ford, J. H., Hicks, D. R. (1992). Corn Growth and Yield in Uneven Emerging Stands. *Journal of Production Agriculture*, 5(1), 185–188. <https://doi.org/10.2134/jpa1992.0185>
- Gupta, S. C., Swan, J. B., Schneider, E. C. (1988). Planting Depth and Tillage Interactions on Corn Emergence. *Soil Science Society of America Journal*, 52(4), 1122–1127.
<https://doi.org/10.2136/sssaj1988.03615995005200040043x>
- Hadas, A. (2004). Seedbed preparation: The soil physical environment of germinating seeds. In R. L. Benech-Arnold & R. A. Sanchez (Eds.), *Handbook of seed physiology: Applications to agriculture*. CRC Press.
- H. M. Hanna, B. L. Steward, L. Aldinger. (2010). Soil Loading Effects of Planter Depth-Gauge Wheels on Early Corn Growth. *Applied Engineering in Agriculture*, 26(4), 551–556.
<https://doi.org/10.13031/2013.32058>
- Kimmelshue, C. L., Goggi, S., Moore, K. J. (2022). Seed Size, Planting Depth, and a Perennial Groundcover System Effect on Corn Emergence and Grain Yield. *Agronomy*, 12(2), 437.
<https://doi.org/10.3390/agronomy12020437>
- Knappenberger, T., Köller, K. (2012). Spatial assessment of the correlation of seeding depth with emergence and yield of corn. *Precision Agriculture*, 13(2), 163–180.
<https://doi.org/10.1007/s11119-011-9235-4>

- Li, H., He, J., Wang, C., Yang, W., Lin, H., Wang, Q., ... Tan, L. (2023a). Research Progress on the Development of the Planter Unit for Furrowing Control and the Depth Measurement Technology. *Applied Sciences*, 13(21), 11884. <https://doi.org/10.3390/app132111884>
- Liu, W., Tollenaar, M., Stewart, G., Deen, W. (2004a). Response of Corn Grain Yield to Spatial and Temporal Variability in Emergence. *Crop Science*, 44(3), 847–854.
<https://doi.org/10.2135/cropsci2004.8470>
- Liu, W., Tollenaar, M., Stewart, G., Deen, W. (2004b). Response of Corn Grain Yield to Spatial and Temporal Variability in Emergence. *Crop Science*, 44(3), 847–854.
<https://doi.org/10.2135/cropsci2004.8470>
- Liu, W., Tollenaar, M., Stewart, G., Deen, W. (2004c). Within-Row Plant Spacing Variability Does Not Affect Corn Yield. *Agronomy Journal*, 96(1), 275–280.
<https://doi.org/10.2134/agronj2004.2750>
- Mahdi, L., Bell, C. J., Ryan, J. (1998). Establishment and yield of wheat (*Triticum turgidum* L.) after early sowing at various depths in a semi-arid Mediterranean environment. *Field Crops Research*, 58(3), 187–196. [https://doi.org/10.1016/S0378-4290\(98\)00094-X](https://doi.org/10.1016/S0378-4290(98)00094-X)
- Murray, J. R. ., Tullberg, J. N. ., Basnet, B. B. . (2006). *Planters and their components : types, attributes, functional requirements, classification and description*. Australian Centre for International Agricultural Research.
- Nafziger, E. D. (1994). Corn Planting Date and Plant Population. *Journal of Production Agriculture*, 7(1), 59–62. <https://doi.org/10.2134/jpa1994.0059>
- Nafziger, E. D., Carter, P. R., Graham, E. E. (1991). Response of Corn to Uneven Emergence. *Crop Science*, 31(3), 811–815. <https://doi.org/10.2135/cropsci1991.0011183X003100030053x>

- Nemergut, K. T., Thomison, P. R., Carter, P. R., Lindsey, A. J. (2021). Planting depth affects corn emergence, growth and development, and yield. *Agronomy Journal*, 113(4), 3351–3360.
<https://doi.org/10.1002/agj2.20701>
- Nielsen, R. L. (2005). Effect of plant spacing variability on corn grain yield. West Lafayette, IN: Purdue University Extension. Retrieved from
<http://www.agry.purdue.edu/ext/corn/research/psv/Update2004.html>
- Novak, L., Ransom, J. (2018). Factors Impacting Corn (&iZea mays&i L.) Establishment and the Role of Uniform Establishment on Yield. *Agricultural Sciences*, 09(10), 1317–1336. <https://doi.org/10.4236/as.2018.910092>
- Parker, J. J., Taylor, H. M. (1965). Soil Strength and Seedling Emergence Relations. I. Soil Type, Moisture Tension, Temperature, and Planting Depth Effects¹. *Agronomy Journal*, 57(3), 289–291. <https://doi.org/10.2134/agronj1965.00021962005700030021x>
- Poncet, A. (2016). *Optimization of Standard Depth Control Systems to Improve Row-Crop Planter Performance in the Southeast US*.
- Poncet, A. M., Fulton, J. P., McDonald, T. P., Knappenberger, T., Shaw, J. N. (2019). Corn Emergence and Yield Response to Row-unit Depth and Downforce for Varying Field Conditions. *Applied Engineering in Agriculture*, 35(3), 399–408.
<https://doi.org/10.13031/aea.12408>
- Poncet, A. M., Fulton, J. P., McDonald, T. P., Knappenberger, T., Shaw, J. N., Bridges, R. W. (2018). Effect of Heterogeneous Field Conditions on Corn Seeding Depth Accuracy and Uniformity. *Applied Engineering in Agriculture*, 34(5), 819–830. <https://doi.org/10.13031/aea.12238>
- Schneider, E. C., Gupta, S. C. (1985). Corn Emergence as Influenced by Soil Temperature, Matric Potential, and Aggregate Size Distribution. *Soil Science Society of America Journal*, 49(2), 415–422. <https://doi.org/10.2136/sssaj1985.03615995004900020029x>

- Seed Distribution in Soil and its Effects on Early Plant Growth. (2015). *Applied Engineering in Agriculture*, 415–423. <https://doi.org/10.13031/aea.31.10846>
- Sharda, A. (2017.). *MF3331 Planter Downforce Technology for Uniform Seeding Depth*.
- Stoll, M., & Saab, I. (2014). Planting depth effects on corn
- Stewart, S., Kitchen, N., Yost, M., Conway, L. S., Carter, P. (2021). Planting depth and within-field soil variability impacts on corn stand establishment and yield. *Agrosystems, Geosciences & Environment*, 4(3), e20186. <https://doi.org/10.1002/agg2.20186>
- Swan, J. B., Kaspar, T. C., Erbach, D. C. (1996). Seed-row residue management for corn establishment in the northern US Corn Belt. *Soil and Tillage Research*, 40(1–2), 55–72. [https://doi.org/10.1016/S0167-1987\(96\)80006-7](https://doi.org/10.1016/S0167-1987(96)80006-7)
- Virk, S. S., Fulton, J. P., Porter, W. M., Pate, G. L. (2020). Row-crop planter performance to support variable-rate seeding of maize. *Precision Agriculture*, 21(3), 603–619. <https://doi.org/10.1007/s11119-019-09685-3>
- Virk, S. (2020). *Investigation of planter downforce in variable field conditions to improve emergence and yield in cotton*.
- Warren, J., Lofton, J., Henry, W., Murley, C., Superintendent, S. (2019). *Soil and Water Conservation Extension Specialist*. Retrieved from <http://blogs.cornell.edu/>
- Web Soil Survey, United States Department of Agriculture-National Resources Conservation Services. (2023).