

Statistical optimization and inequality assessment of corn planting: an analysis of seeding depth
and spacing uniformity

by

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Abstract

Sowing is a fundamental planting operation in a growing season, and its primary purpose is to consistently place the seed at a target depth with uniform spacing. Both seeding depth and plant-to-plant spacing are key factors that govern the success of crop establishment in corn. Inappropriately positioned seeds can lead to poor seedbed conditions significantly influencing crop establishment and substantially reducing yield potential. Modern planters are designed to effectively singulate and precisely position seeds in a furrow ensuring adequate seed-to-soil interaction. Inclement weather conditions often limit planting windows, and higher planting speed is one of the management strategies farmers resort to for compensation. However, such interplay of planter operation settings can result in sub-optimal seeding depth and variable spacing, leading to poor agronomic outputs. The purpose of this study was twofold: first to identify the optimal operational parameters for a row crop planter that consistently achieves target seeding depth. Second, to assess the impact of such parameters on within-row spacing variability and evaluate yield disparities.

Field experiments were conducted in a split-plot arrangement with downforce levels ranging from 100—325 lbf and planting speeds spanning from 5—10 mph. A second-order full-quadratic model was defined, and a face-centered central composite design was employed to evaluate the relationship between seeding depth and operation parameters—downforce and speed. Spacing variability was studied using metrics based on distribution moments as well as the Gini index and Lorenz curves. The impact of spacing inequality on yield outcomes at a plant level was quantified with regression techniques.

Analysis reveals distinct downforce and speed requirements across sections of a planter—track, non-track, and wing. Intermediate planting speed (7.1—7.5 mph) coupled with moderate

downforce level (222—232 lbf) yielded minimal bias from the target seeding depth (2 in.) in non-track and wing sections. The track section minimized bias at a relatively lower planting speed and downforce level. Lower planting speeds coupled with moderate downforce settings minimized spacing inequality as evidenced by lower G-spacing values, and relatively minimal deviations in Lorenz curves. Yield outcome at the plant level was negatively and significantly ($\alpha = 0.05$) correlated with within-row variability of corn plant spacing. For each unit increase in plant spacing variation, a reduction of 9.13 g per plant was observed. Other non-ideal spacing outcomes like missing plants and multiples also negatively impacted corn yield.

Findings indicate a direct influence of operation settings—planting speed and applied downforce, on seeding depth as well as spacing uniformity. The influence on spacing uniformity, in turn, translates to a significant impact on corn yield. The extent of yield loss is accentuated as inequality in spacing rises. These insights underscore the need for prudent management of operational settings.

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Dedication

To my father and mother, with profound gratitude for their enduring support and encouragement.

Chapter 1 - Introduction

The word “statistics” has its origin in the German “Statistik”. It can take both singular and plural forms. In singular form, it refers to a field of study, as one would refer to engineering, medical science, or agriculture. When plural it refers to data or a collection of data. The field of statistics is a combination of both theoretical mathematics and methods that govern their application (Hoshmand, 1997).

The contribution of statistics to the evolution of agricultural research is substantial, particularly when the cause and effects are not apparent to the researcher. In recent times, the need for a consistent measurable reference to shape agricultural policies, the necessity of predictive capabilities to analyze impacts, and the desire to leverage information from data have developed quantitative approaches to statistics. Today, agricultural practitioners achieve continual improvement in breeding practices and understand the nutritional needs of livestock by analyzing data. Research institutions in major universities use sound statistical procedures like regression analysis and estimate the functional relationship between variables with quantified uncertainty. Agricultural engineers implement statistical methods to improve machine performance, understand the impact of machinery implements on agronomic outputs, and compare yields (Booth et al., 1981; Hoshmand, 1997).

This study is an attempt to apply statistical principles to both optimize the performance of a row crop planter and understand its impact on agronomic outcomes. The thesis is structured into two chapters:

1. Optimizing planter parameters using response surface methodology for ideal corn seeding depth
2. Assessing corn spacing inequality and yield disparities using Lorenz curves and the Gini index

Chapter 2 - Optimizing Planter Parameters Using Response Surface Methodology for Ideal Corn Seeding Depth

Introduction

Sowing is one of the crucial planting operations in a growing season, and its primary purpose is to place the seed at a certain depth and spacing within the seedbed. Poor seedbed conditions can significantly influence crop establishment—a process that involves seed germination, seedling emergence, and early shoot growth—and substantially impact final yield potential (Özmerzi et al., 2002; Poncet et al., 2019). Choosing an appropriate seeding depth and precisely positioning the seed is a complex challenge in planting management. Seeding depth is the vertical distance measured from the soil surface to the location of the seed after planting. ISO 7256-1:1984 outlines a conventional method of acquiring seeding depth that requires removing soil layers with a graduated scrapper until the top surface of the seed is visible. An alternative approach involves measurements after excavating a newly emerged seedling to determine the depth (Mapoka, 2018; Srivastava et al., 2006). Early and accurate assessment of seeding depth is essential as it directly affects the proper crop development (Grassbaugh & Bennett, 1998; Mapoka, 2018).

Optimum seeding depth is where moisture, temperature, oxygen availability, and all other environmental factors converge favorably to promote germination and emergence. It is the depth at which the greatest number of seedling emergence occurs (Chan et al., 1969; Masilamani et al., 2023). The choice of burial depth can significantly affect edaphic factors that are key determinants of successful germination in many plant species. Variation in seed sizes among species results in different energy reserves within the seed, influencing its germinative potential. In practice, farmers

typically plant larger seeds at deeper depths compared to smaller seeds (Ali & Idris, 2015; Bond et al., 1999; Kimmelshue et al., 2022; Lamb & Johnson, 2004; Masilamani et al., 2023).

Crop emergence is a vital phenological process by which a germinated seed pushes through the soil surface as a visible and identifiable seedling. It represents a complex and continuous phase in a plant's life cycle when the non-renewable energy reserves of the seed wane and photosynthetic autotrophism initiates (Banerjee et al., 2021; Forcella et al., 2000; Morrison & Gerik, 1985). The conventional standard method of quantifying emergence is manually counting or scoring visible seedlings at regular intervals. Emergence estimation at early growth stages is an indirect measure of plant density and a predictor of crop success. Producers can use these assessments to screen genotypic traits and make informed crop management decisions, facilitating resource optimization and output maximization (Banerjee et al., 2021; M. Liu et al., 2023).

Early, uniform, and prolific emergence is highly desirable in crop production as it shortens the vulnerable seedling phase, extends the growing season, and maximizes potential yields (Carter et al., 1990; Stewart et al., 2021; Wanjura, 1982). Uniform emergence usually results from consistent and optimal depths across the field. Studies aimed at improving the understanding of crop response to planting depth demonstrate that inconsistent emergence patterns stem from suboptimal choice and variations in seeding depth (Özmerzi et al., 2002; Silva et al., 2004; Virk et al., 2021). As corn (*Zea mays* L.) seeds imbibe water within the first 48 hours of planting (B. Nielsen, 1995), good seed-to-soil contact is necessary to facilitate the transfer of moisture and nutrients to the seed zone. Past findings suggest that soil temperatures between 20—30 °C combined with a 50 % available water capacity (B. Nielsen, 1995) are ideal for timely emergence (Nemergut et al., 2021; Schneider & Gupta, 1985; Stewart et al., 2021). Given these conditions, the mesocotyl elongates to push the coleoptile to the soil surface, where it unwraps, allowing the

true leaves to emerge (Abendroth et al., 2011; B. Nielsen, 2020). Field experiments have shown that the optimal choice of seeding depth can increase emergence in corn plants by 2.4—5.4 % (Knappenberger & Köller, 2012).

Özmerzi et al. (2002) examined the effects of three different depths—1.57, 2.36, and 3.15 in.—on emergence time, emergence rate, and depth uniformity. The findings concluded that 2.36 in. was the optimum depth, as evidenced by the least seeding depth uniformity (CV: 4.29 %, 4.93 %) and maximum emergence rate index. Molatudi & Mariga (2009) assessed the influence of varying planting depths—1.97, 3.94, 5.91, and 7.87 in. At 1.97 in. depth, corn emergence was earliest and peaked within 12 days after planting; 18 days after planting, emergence was over twofold greater than 7.87 in. Itabari et al.'s (1993) field experiment at three planting depths, 0.98, 2.95, and 4.92 in., observed that germination and emergence were best at 2.95 in. Poncet et al. (2019) reference Monsanto (2009) and Thomison (2012) to suggest that standard depth recommendations for corn planting typically range from 1.73 to 2.48 in. Stewart et al. (2021) emphasized that beyond these evidence-based standards, it is also essential to consider the spatial variability of soil conditions like texture and landscape. Stewart et al.'s (2021) field experiments in central Missouri established that planting corn in alluvial soil at 2.99 in. often resulted in uniform and timely emergence. Planting at 1.42 in. yielded the least uniform emergence, particularly in fine-textured soil under warm conditions. Badua et al. (2021), citing Fancelli's (2000) work, suggested a seeding depth between 1.18 to 1.97 in. for clay soils and 1.57 to 2.36 in. for sandy soils, which generally warm more rapidly.

Planting corn at shallower depths (less than 1.50 in.) is advised against, as it results in poor crop growth due to the lack of adequate moisture (at ideal field conditions) at the topsoil layer (Abendroth et al., 2011; Coronel et al., 2020; Nafziger, 2009; B. Nielsen, 2010). Excessively

shallow planting exposes the seed to thermal stress, leaves the crown exposed, and impacts the development of nodal roots (Sharma et al., 2019). If nodal roots form close to the soil surface, it might result in a "rootless" or "floppy" corn syndrome under arid conditions (Sandell et al., 2015). Seeds closer to the topsoil are prone to chilling injury due to limited buffering against temperature and moisture fluctuations and are subject to poor seed-to-soil contact. Consequently, it results in non-uniform emergence, extended emergence periods, and poor crop establishment (Nemergut et al., 2021). Stewart et al. (2021) studied planting depths ranging from 1.5 to 2.99 in. for three years. Results show that uniformity of emergence was consistently poorest at the shallowest depth of 1.5 in., regardless of field conditions. Compared to the deeper planting depths, the emergence window extended by an average of 9 days (2017), causing a yield loss of 2.8 Mg ha⁻¹.

Increasing planting depth can improve consistency in soil water content and temperature within the seed furrow, directly influencing the physiochemical properties of the soil microcosm. It also reduces predation risks, prevents desiccation, and averts the possibility of wind or water washout (Sáenz Rodríguez & Cassab, 2021). Furthermore, deeper planting allows corn roots to access more moisture, increasing emergence uniformity and yield (Nemergut et al., 2021; Poncet et al., 2019). Pommel (1990) observed accelerated growth of deeper (2.76 in.) sown corn, while shallow-planted (0.79 in.) corn experienced a significant delay in development. Pommel attributed the phenomenon to better availability and efficient use of resources at deeper depths. Knappenberger & Köller (2012) planted corn at varying depths—1.57, 1.97, 2.36, 2.76, 3.15, and 3.54 in.—over three years to investigate their influence on crop emergence and grain yield. Medium (2.36—2.76 in.) and deep seeding depth (3.15—3.54 in.) resulted in significantly higher emergence. Compared to shallow-planted (1.57—1.97 in.) corn, emergence was greater by 4.4 % in 2006, 1.2 % in 2007, and 1.5 % in 2008. The increase in emergence also translated to increased

yield. However, wet conditions at excessively deeper depths can suppress emergence by limiting seedling vigor (Nemergut et al., 2021). As the seedling attempts to emerge, the mesocotyl has to traverse an increased distance for the coleoptile to penetrate the soil surface, often leading to delayed and uneven emergence (Blacklow, 1972). Studies report decreased physiological factors like seedling vitality, leaf number, and plant height when the seeding depth is 5.91 in. or higher (Molatudi & Mariga, 2009; Mutema, 2015).

At ideal soil moisture conditions, corn seeding depth recommendation spans 1.5—2.0 in. for most soil types (Abendroth et al., 2011; Coronel et al., 2020; Knappenberger & Köller, 2012; Nafziger, 2009; B. Nielsen, 2010). Validated with field-scale research, guidelines for midwestern states from University Extensions and industry sources align with these specifications (Cox & Cherney, 2015; Nemergut et al., 2021; Thomison, 2012). In northeast Kansas, for a planting window between April 15 and May 10 (James P Shroyer et al., 1996), when the soil temperatures are 20—30 °C, 2.0 in. is considered the optimal seeding depth (Jeschke, 2021; Mishler, 2021; B. Nielsen, 2021).

Planting at a set soil depth involves opening a furrow in the soil to place the seed, followed by a proper closure to ensure adequate seed-to-soil interaction. Besides considering spatial variability in soil properties, it necessitates precise configuration and skillful operation of planting equipment (Morrison & Gerik, 1985; Virk et al., 2021). In the United States, operators set the planting depth of row-crop planters by adjusting the T-handle, and gauge wheels mounted on each unit maintain this depth as they roll alongside the furrow (Poncet et al., 2019; Virk et al., 2021). One measure of a planter's performance is its ability to maintain a consistent seeding depth throughout the entire field. Modern precision planters feature hydraulic downforce control on each row, along with real-time monitoring and adjustment capabilities. Downforce is the supplemental

load on the gauge wheel in addition to the row unit's inherent weight that allows the opening discs to open a clean furrow (Poncet et al., 2019; Soignier et al., 2022). Studies mention it as one of the significant planting variables, which, if selected appropriately, maximizes planter performance and results in higher crop emergence (Badua et al., 2021; Hanna et al., 2008; B. Nielsen, 1995; Virk et al., 2021).

Inclement weather conditions often limit the planting window, rendering the fields inaccessible to agricultural machinery. Farmers adopt different management strategies to compensate for the reduced planting days, which include opting between hybrids, tailored field preparation, and higher planter speeds to cover more acreage in fewer hours (Mishler, 2021; Urban, 2015; Van Duc Long et al., 2017). However, ensuring precise and consistent seed placement while operating planters at higher speeds poses a considerable challenge. Research indicates that planting at faster speeds increases row-unit vibration, often resulting in shallow placements and compromising uniformity in seeding depth (Badua et al., 2021; Quanwei et al., 2017; Silveira et al., 2011). In Brandelero et al.'s (2015) experiments, with planter speeds ranging from 2.11 to 5.72 mph, the maximum speed of 5.72 mph led to a reduction in seed sowing depth by 0.59 in., subsequently causing a 14 % rise in exposed seeds. Emrah Kuş (2021) observed a 10 % decrease in emergence correlated with increasing planter speeds of 2.49, 3.42, and 4.91 mph. Nielsen (1995) reported a reduction in yield from 1.71 to 4.23 Mg ha⁻¹ for every mph increase in planting speed. The interplay between downforce settings and planter speed affects seeding depth. A combination of inadequate downforce on the row-unit and elevated planting speeds can lead to row-unit bounce, resulting in inconsistent seeding depths (Badua et al., 2018; Mishler, 2021). Increased downforce results in deeper planting, but excessive downforce may cause sidewall compaction, potentially limiting crop development (Hanna et al., 2008; Karayel & Šarauskis, 2011).

Consequently, improper downforce settings impact planting efficacy, leading to poor agronomic outcomes and causing financial implications associated with equipment wear. Therefore, this study aims to identify adequate downforce settings, regardless of planting speed, using response surface maps to optimize planter performance. A secondary objective is to assess the variations of these optimal settings across different planter sections.

Materials and Methods

Site Description and Planter Setup

The study was conceptualized at FarmsLab (Fusing Automation and Robotics in Ag Machine Systems), Kansas State University. Field experiments were conducted for planting season 2022 in Field A (39°18'11.0"N, 97°10'29.8"W) and for 2023 in Field B (39°20'56.4"N, 97°10'44.7"W) Clay Center, KS. The elevation from sea level was about 1300 ft and 1020 ft, respectively. Site characteristics for soil texture were obtained from the USDA Web Soil Survey; Table 2.1 provides comparative information on the soil characteristics for both fields. The soil texture for Field A is a silty clay loam, whereas Field B exhibits a silt loam texture. Climatic conditions during both years were comparable with the average air temperature ranging from 10°C to 23°C for 2022 and 8°C to 21°C for 2023 within the planting window (April 15—May 20). Experiments were aligned with standard farming norms adopted by local farmers to ensure consistency.

Researchers planted corn in Field A on May 12, 2022, with a 16-row JD 1775NT16Row30 ExactEmerge™ (Deere & Company, Moline, IL, hereafter referred to as 16-RP). Field B was planted with a 24-row JD 1775NT 24Row30 ExactEmerge™ (Deere & Company, Moline, IL, hereafter referred to as 24-RP) on April 24, 2023. The row spacing for both planters was 30 in.,

and every row was equipped with a closed-loop hydraulic downforce system. Both planters used a "Tru-Vee" double disc opener and deposited seeds in the trench using a BrushBelt™ seed delivery system. The depth setting for each row unit was selected by adjusting the position of the T-handle. For the 16-RP, the track section included row units 6 through 11; units 4, 5, 12, and 13 constituted the non-track section; and units 1 to 3 and 14 to 16 encompassed the wing section. Similarly, for the 24-RP, the track section included units 10 through 15; units 5 to 9 and 16 to 20 formed the non-track section; and units 1 to 4 and 21 to 24 comprised the wing section.

Table 2. 1 Soil characteristics for experimental sites: Field A and Field B

Properties	Field A (2022)	Field B (2023)
Soil series	Crete silty clay loam	Crete silt loam
Slope	3—7%	1—3%
Toposequence	Hillslopes	Interfluves
Available water supply	High (266.7 mm)	High (269.2 mm)
Drainage class	Moderately well drained	Moderately well drained
Runoff class	High	Medium
Tillage	Non-tillage	Non-tillage
Irrigation	Non-irrigation	Pivot irrigation
Precipitation (Annual Total)	603 mm	531 mm
Soil temperature (51 mm, min-max)	11°C—15°C	8°C—14°C

Study Design and Data Collection

The study was arranged in a split-split plot design (Montgomery, 2013) with three replicates (three geographical plot locations, each 17 ft long) for both the years 2022 and 2023. In 2022, the whole plot factor was downforce with three levels (120, 220, and 320 lbf), the sub-plot factor was speed with three levels (6, 7.5, and 10 mph), and the sub-sub-plot factor was section with three levels (track, non-track and wing). In 2023, the whole plot factor was also downforce with four levels (100, 175, 250, and 325 lbf), speed was the sub-plot factor with three levels (5, 7.5, and 10 mph), and sub-sub-plot factor was section with three levels (track, non-track and wing).

Seeding depth measurements were determined by excavating the soil around the emerged seedling (stage: V1, one visible leaf collar) in each treatment strip. Excess soil was carefully cleared to uncover the seed, and a flat ruler was positioned along the furrow to reference the surface level. A digital vernier caliper's (resolution: 0.01 mm) depth blade was extended to the base of the seed to record the sowing depth (ISO 7256, 1984; Jeschke, 2021).

Three quantitative indicators, namely bias, precision, and accuracy, were obtained by processing the depth measurements. Bias is the extent to which observed measurements systematically deviate from the actual true value. It was calculated as a difference between the average of measurements on a sample (treatment combination) and its accepted reference—target depth (Bruno Walther et al., 2005). On the other hand, precision is independent of the true value and assesses how similar the measured values are to each other. Standard deviation (statistical variability in the sample) was quantified as precision. Accuracy refers to the closeness of a measurement to its true value and is determined by considering both the bias and precision. Eq. (1), Eq. (2), and Eq. (3) provide the formulas for these quantitative performance indicators (Borgan et al., 2020; Bruno Walther et al., 2005; Mishler, 2021).

$$Bias (B_i) = \frac{1}{n_i} \sum_{j=1}^n |d_{ij} - d_t|, \quad (1)$$

$$Precision (P_i) = \sqrt{\frac{1}{n_i} \sum_{j=1}^n (d_{ij} - \bar{d}_i)^2}, \quad (2)$$

$$Accuracy (A_i) = \frac{1}{n_i} \sum_{j=1}^n (d_{ij} - d_t)^2, \quad (3)$$

where $i = 1, 2, 3 \dots$, is the treatment strip sampled, n_i is the total number of samples in the strip, d_{ij} is the j^{th} measurement from the i^{th} strip, and d_t is the optimal target depth—2 in.

Statistical Analysis

Spatial dependency among observations is often expected in data collected from heterogeneous field conditions (Knappenberger & Köller, 2012; Poncet et al., 2018). An assessment of spatial dependency among the seeding depth observations was carried out by analyzing the residuals of the linear model Eq. (4) using experimental variograms. It was followed by a more formal approach of incorporating spatial correlation structures in the standard linear model. Exponential, gaussian, rational quadratic, linear, and spherical structures were evaluated, and the best model was judged based on the Akaike Information Criterion (AIC) (Alain F. Zuur et al., 2009; Diggle & Ribeiro, 2007).

$$Y_{ijk} = \beta_0 + \sum_{i=1}^3 \beta_i X_i + \sum_{i,j=1}^3 \beta_{ij} X_i X_j + \varepsilon_{ijk}, \varepsilon_{ijk} \sim N(0, \sigma^2), \quad (4)$$

where Y_{ijk} is the quantitative response variable—seeding depth, X_i and X_j are design factors, β_0 is the intercept, β_i the linear coefficient and β_{ij} the interaction coefficient. The correlation structure can be expressed as Eq. (5)

$$\text{Cor}(Y_{s_i}, Y_{s_j}) = \begin{cases} 1 & \text{if } s_i = s_j \\ h(s_i, s_j, \rho) & \text{else,} \end{cases} \quad (5)$$

where Y_{s_i}, Y_{s_j} are the observations at spatial locations i and j , $h()$ is a parameterization function that defines the correlation between these two locations, and ρ is the strength of the correlation.

A mixed effects linear model was fit using the "*nlme*" package (version: 3.1-164) (Pinheiro et al., 2023) in R version 4.3.1 (R Core Team, 2023) for analysis of variance. Replicates, downforce, speed, section, and their interactions were considered fixed effects. Random effects included replicate $\times$ downforce (whole plot error), replicate $\times$ downforce $\times$ speed (sub-plot error), and replicate $\times$ downforce $\times$ speed $\times$ row (residual error) were the random effects. Tukey's HSD test was applied for post-hoc pairwise depth comparison between groups at significance level $\alpha = 0.1$. Graphical methods were used to verify normality and homoscedasticity of residuals.

Response Surface Methodology

Response surface Methodology (RSM) is an integration of mathematical and statistical techniques designed to optimize a response through sequential experimentations (Myers, 2016). It was developed by Box and Wilson (1951) to aid in the improvement of industrial processes. RSM aims to identify a feasible combination of process settings for which the response is optimized—maximized, minimized, or equal to a specific target (Dean et al., 2017). A linear or a first-order model may not always be adequate to predict the mathematical relationship between a response and independent process variables. A higher order, usually a quadratic polynomial model, can adequately approximate the functional relationship between variables for most industrial applications (Jambrak, 2011; Myers, 2016).

A second-order polynomial regression equation, Eq. (6), was defined to assess the relationship between the response (bias, precision, accuracy) and the planter operation settings (downforce, speed).

$$Y = f(X) = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \sum_{j \geq i}^k \beta_{ij} X_i X_j + \sum_{i=1}^k \beta_{ii} X_i^2, \quad (6)$$

where Y is the response variable; X_i and X_j are factors that influence the response, β_0 is the intercept; β_i , β_{ij} and β_{ii} are the coefficients of linear, interaction, and quadratic terms, and k is the number of factors studied.

This study employs a face-centered central composite design (CCD) for response surface analysis. The total number of runs (N) for CCD included standard 2^k factorial runs, $2k$ axial runs, and n_c central runs, each replicated three times. Twenty-seven experimental runs were obtained for each section from Eq. (7). The distance of the axial points from the center of the design, α , is set to 1.

$$N = 2^k + 2k + n_c. \quad (7)$$

Table 2. 2 Independent variable levels in actual measurements and coded units

Factors	Code	Experiment	Levels of coded variables				
			$-\alpha$	Low	Medium	High	$+\alpha$
			-1	-1	0	1	1
Downforce (N)	X_1	2022	534	534	979	1423	1423
			445	445	945	1446	1446
Speed (km h ⁻¹)	X_2	2023	9.7	9.7	12.8	16.1	16.1
			8.0	8.0	12.1	16.1	16.1

Eq. (8) maps the actual values of the parameters (x_i) to their coded values (X_i), and are given in Table 2.2. The range of parameters was selected based on standard farming practices and past studies. The central composite design with experimental results is presented in Table 2.3.

$$X_i = 2 \left(\frac{x_i - x_{mid \text{ value}}}{x_{range}} \right), \quad (8)$$

where $x_{mid \text{ value}} = \frac{x_{min} + x_{max}}{2}$ and $x_{range} = x_{max} - x_{min}$.

Table 2. 3 Central Composite Design in coded and actual measurement units for all three planter sections

Code		Response (2022)									Response (2023)								
X_1	X_2	Bias			Precision			Accuracy			Bias			Precision			Accuracy		
		N	T	W	N	T	W	N	T	W	N	T	W	N	T	W	N	T	W
-1	-1	0.22	0.18	0.19	0.18	0.17	0.18	0.07	0.06	0.05	0.21	0.31	0.33	0.10	0.09	0.11	0.05	0.11	0.14
+1	-1	0.16	0.32	0.17	0.14	0.27	0.15	0.06	0.17	0.05	0.33	0.17	0.25	0.12	0.08	0.10	0.23	0.04	0.07
-1	+1	0.39	0.37	0.40	0.19	0.40	0.15	0.19	0.18	0.25	0.57	0.42	0.33	0.18	0.08	0.16	0.36	0.19	0.15
+1	+1	0.26	0.32	0.34	0.28	0.28	0.28	0.08	0.20	0.14	0.33	0.21	0.26	0.03	0.05	0.11	0.14	0.06	0.11
$-\alpha$	0	0.12	0.18	0.22	0.12	0.13	0.22	0.02	0.06	0.07	0.28	0.33	0.45	0.12	0.09	0.06	0.11	0.15	0.24
$+\alpha$	0	0.13	0.24	0.27	0.10	0.28	0.28	0.02	0.13	0.12	0.23	0.40	0.41	0.07	0.10	0.14	0.07	0.19	0.22
0	$-\alpha$	0.24	0.21	0.33	0.16	0.21	0.19	0.07	0.08	0.12	0.07	0.28	0.26	0.04	0.08	0.11	0.01	0.10	0.08
0	$+\alpha$	0.20	0.29	0.29	0.18	0.30	0.28	0.06	0.14	0.13	0.22	0.37	0.21	0.03	0.12	0.08	0.06	0.16	0.06
0	0	0.20	0.12	0.13	0.23	0.14	0.16	0.05	0.03	0.03	0.11	0.14	0.08	0.09	0.08	0.08	0.01	0.03	0.01
0	0	0.20	0.28	0.11	0.20	0.08	0.14	0.04	0.08	0.02	0.33	0.25	0.39	0.02	0.07	0.09	0.11	0.07	0.16
0	0	0.07	0.17	0.29	0.08	0.14	0.28	0.01	0.05	0.10	0.18	0.16	0.10	0.09	0.11	0.09	0.04	0.04	0.01

Results and Discussion

Descriptive statistics by each treatment combination across all three planter rows are given in Table 2.4 and Table 2.5 for experimental years 2022 (16-RP) and 2023 (24-RP), respectively. For 2022, a maximum seeding depth of 2.16 in (SD: 0.13) was observed at 320 lbf and 6 mph, whereas the shallowest seeding depth of 1.73 in. (SD: 0.20) was observed at 120 lbf and 10 mph. Results indicate a trend where increased downforce consistently leads to deeper average seeding depths, while higher planting speeds have a slightly negative effect. The standard deviation of seeding depth varies with the interplay of downforce and speed without a clear trend; however, lower speeds tend to be more consistent. Among the three planter sections, the non-track section exhibited the highest

level of uniformity in seeding depth, followed by track and wing.

Similarly, for 2023, a maximum seeding depth of 2.25 in (SD: 0.37) was obtained at 325 lbf and a relatively moderate planting speed of 7.5 Mph. The shallowest seeding depth was 1.65 in. (SD: 0.18) at 100 lbf and 7.5 mph. Again, a trend of higher downforce leading to deeper average seeding depth was observed; however, the variability in seeding depth also increased with increasing downforce. The downforce applied also influenced the impact of planting speed on average depth and its consistency. The uniformity of seeding depth across non-track and track sections showed comparable levels, while the wing section demonstrated notably lower consistency.

Table 2. 4 Summary statistics of seeding depth at different downforce and speed settings across all planter rows for the experimental year 2022.

Speed (mph)	Downforce (lbf)									
		120			220			320		
		N	T	W	N	T	W	N	T	W
6	Mean	2.01	1.91	1.97	2.14	1.93	2.23	2.13	2.21	2.14
	SD	0.22	0.06	0.17	0.12	0.15	0.19	0.11	0.25	0.03
7.5	Mean	2.00	1.84	2.10	1.97	2.12	2.04	2.03	1.85	2.00
	SD	0.06	0.12	0.07	0.02	0.18	0.12	0.10	0.14	0.16
10	Mean	1.65	1.94	1.60	1.95	2.09	1.85	2.02	1.80	2.11
	SD	0.22	0.09	0.30	0.18	0.07	0.17	0.07	0.29	0.24

Table 2. 5 Summary statistics of seeding depth at different downforce and speed settings across all planter rows for the experimental year 2023.

Speed (mph)	Downforce (lbf)												
		100			175			250			325		
		N	T	W	N	T	W	N	T	W	N	T	W
5	Mean	1.85	1.69	1.68	1.93	1.71	1.73	1.98	1.73	1.74	2.20	1.91	1.95
	SD	0.13	0.10	0.15	0.05	0.15	0.03	0.06	0.13	0.04	0.51	0.17	0.30
7.5	Mean	1.73	1.67	1.56	1.72	1.68	1.69	1.85	1.98	1.85	2.18	2.26	2.20
	SD	0.13	0.22	0.20	0.07	0.19	0.12	0.20	0.23	0.20	0.22	0.41	0.48
10	Mean	1.49	1.57	1.99	1.75	1.69	1.77	1.78	1.65	1.97	1.67	1.78	1.74
	SD	0.12	0.05	0.42	0.22	0.06	0.03	0.12	0.05	0.26	0.19	0.11	0.23

Table 2. 6 Comparative evaluation of standard and spatial depth model performance: AIC, range, and nugget metrics for experimental years 2022 and 2023.

Model	Experiment 2022			Experiment 2023		
	AIC	Range	Nugget	AIC	Range	Nugget
Standard	43.09	-	-	96.32	-	-
Exponential	47.09	0.07	0.10	94.56	6.11	0.16
Gaussian	47.09	0.32	0.10	94.35	6.37	0.20
Rational Quadratic	47.09	0.00	0.16	94.16	5.25	0.25
Linear	47.09	1.52	1.00	-	-	-
Spherical	47.09	1.41	0.15	94.76	12.61	0.10

Note: The model with linear correlation structure for the experimental year 2023 failed to converge.

AIC, range, and nugget for the standard linear model and five different spatial models are presented in Table 2.6. For the experimental year 2022, no significant spatial autocorrelation was observed, and the standard model had the lowest AIC (43.09). For 2023, the spatial model with a rational quadratic correlation structure has the smallest AIC (94.16) value with a nugget of 0.25 and a range of 5.25. Hence, the standard linear model (2022) and a spatial model with rational quadratic correlation (2023) were used to fit the data and perform subsequent statistical tests, including ANOVA and post hoc comparisons of means.

In 2022, seeding depth was significantly influenced by downforce ($p < 0.1$, $F = 5.87$), speed ($p < 0.01$, $F = 8.77$), and their interaction downforce $\times$ speed $\times$ row ($p < 0.05$, $F = 2.80$) with the mixed effects model accounting for 47.3 % of the variability in seeding depth. Likewise, in 2023, significant factors affecting seeding depth included downforce ($p < 0.05$, $F = 5.40$) and the interaction speed $\times$ row ($p < 0.001$, $F = 6.24$), with the model explaining 53.6 % of the variability in seeding depth was explained by the model.

Following the mixed effects model analysis, a post-hoc pairwise comparison with Tukey adjustment was performed, and the results are summarized in Table 2.7. In 2022 (Figure 1), planted with a 16-RP, at 120 lbf downforce settings, mean seeding depth decreased significantly from 1.96 to 1.73 in. (11.7 %) as planter speed increased from 6 mph to 10 mph. At 220 lbf downforce

settings, although a trend of decreasing depth was observed with increasing speed, it was not statistically significant. At the highest downforce setting of 320 lbf and a planter speed of 6 mph, the mean seeding depth was 2.16 in., which significantly decreased to 1.96 in. (9.2 %) at 7.5 mph. However, the depth remained identical upon further increase to 10 mph.

Table 2. 7 Pairwise comparison for interaction effects of downforce and planter speed on seeding depth

Speed (Mph)	Experiment 2022			Speed (Mph)	Experiment 2023			
	Downforce (lbf)				Downforce (lbf)			
	120	220	320		100	175	250	325
6	1.96 a	2.16 a	2.16 a	5	1.74 a	1.79 a	1.81 a	2.03 ab
7.5	1.98 a	2.05 a	1.96 b	7.5	1.65 a	1.70 a	1.90 a	2.21 a
10	1.73 b	1.96 a	1.98 b	10	1.70 a	1.75 a	1.80 a	1.74 b

Note: Mean followed by the same grouping alphabet cannot be shown as different at $\alpha=0.1$.

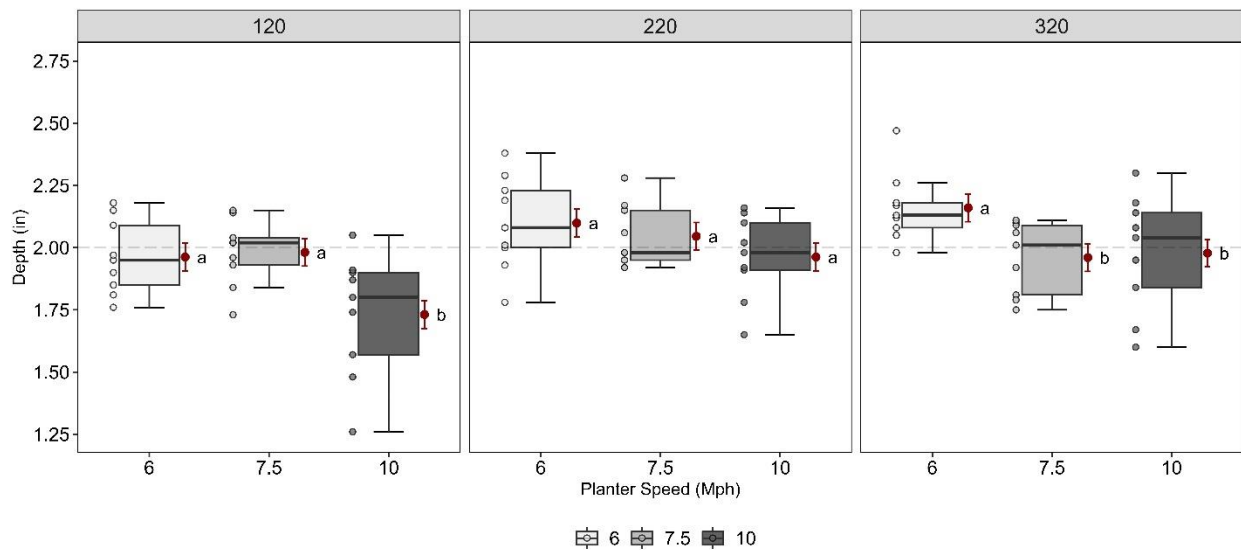


Figure 2. 1 Variation in seeding depth across different planter speeds, segmented by downforce levels (120, 220, and 320 lbf); year 2022, 16-row planter. Boxplots show the depth distribution; adjacent error bars indicate the estimated mean and associated standard errors. Mean followed by the same grouping alphabet cannot be shown as significantly different at $\alpha=0.1$ within each downforce category.

For 100 lbf and 175 lbf, downforce settings in the 2023 experiment (Figure 2), planted with 24-RP, depth indicated a decreasing trend with increasing planter speed. At 250 lbf, a maximum

seeding depth of 1.81 in. was observed at the intermediate speed of 7.5 mph, which is approximately 4.9 % greater than the depth at 5 mph and 5.6 % greater than at 10 mph. Similar variations were observed at 325 lbf downforce settings, with a maximum depth of 2.21 in. achieved at 7.5 mph. A significant reduction in depth to 1.74 in. (21.2 %) occurred as the speed increased to 10 mph.

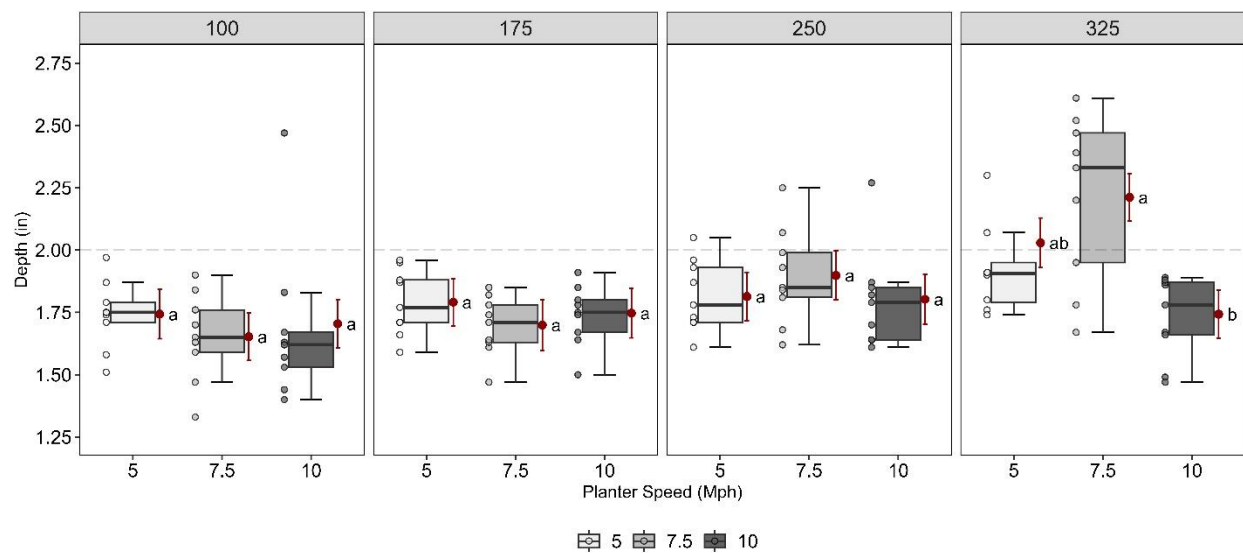


Figure 2. 2 Variation in seeding depth across different planter speeds, segmented by downforce levels (100, 175, 250, and 320 lbf); year 2023, 24-row planter. Boxplots show the depth distribution; adjacent error bars indicate the estimated mean and associated standard errors. Mean followed by the same grouping alphabet cannot be shown as significantly different at $\alpha=0.1$ within each downforce category.

Fitting Optimization Models

The CCD presented in Table 2.3 was analyzed using a second-order full quadratic model to explore the relationship between bias, precision, and accuracy in seeding depth as influenced by two primary factors—downforce and planter speed. The full quadratic model allowed a comprehensive analysis of non-linearities and higher-order interactions. Additionally, it enabled simultaneous consideration of multiple responses through overlaid contour plots. For each planter section, mathematical equations were developed to assess each response as a polynomial function

of downforce and speed. The fitted models' significance and adequacy were evaluated using F -tests and lack-of-fit tests, respectively, at a 95 % confidence level. Table 2.8 and Table 2.9 detail the outcomes of these analyses, including the coefficient of determination (R^2) values that measure the proportion of variance explained by each model. A combination of graphical assessments and formal statistical tests verified model assumptions. Shapiro-Wilk test of normality and the Breusch-Pagan test of residuals at a confidence level of 95 % do not reveal strong deviations from normality or homoscedasticity for all models. Although statistical significance was not met for every model at the conventional 95 % confidence level, the relatively good R^2 values, fulfillment of underlying assumptions, model adequacy, effect size, and direct relevance to field applications suggest a practical significance. Therefore, the second-order full quadratic model was used to interpret optimal planter performance.

Non Track Section

Figure 3 provides a comparison of the changes in bias, precision, and accuracy of seeding depth in response to changes in speed and downforce for two different experimental setups, using a 16-RP in 2022 and a 24-RP in 2023, both in non-track sections. Figure 3(a), corresponding to 16-RP, shows an increase in bias as speed increases, notably beyond 8 mph. Increasing downforce decreases bias at lower to moderate speeds; however, this beneficial effect diminishes at higher speeds. Figure 3(b), for the 24-RP, reveals that the bias gradient with respect to changes in speed is relatively steeper, implying that 24-RP is more sensitive to speed changes than 16-RP. Canonical path analysis reveals that a downforce of 222 lbf combined with a planter speed of 7.5 mph yields a minimum bias of 0.14 in. (1.86—2.14 in. seeding depth) for the 16-RP. The model explains 61 % of the variability in bias. Similarly, for the 24-RP, applying a downforce of 232 lbf and a speed

of 7.3 mph results in a bias of 0.16 inches (1.84—2.16 in. seeding depth), and the model accounts for 76 % of the variability in bias.

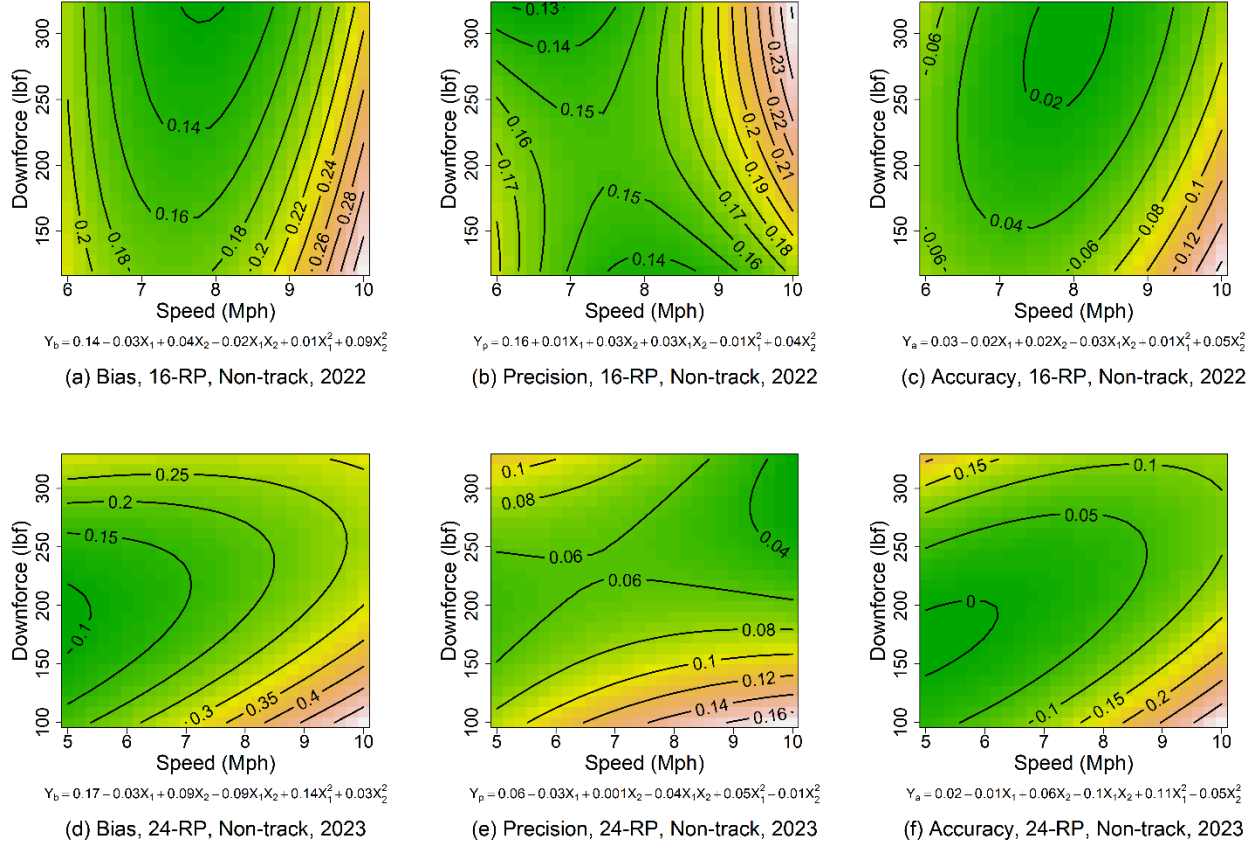


Figure 2.3 Contour plots to illustrate the combined effects of downforce (lbf) settings and planting speed (mph) on bias, precision, and accuracy of seeding depth for the non-track section of the planter. Plots (a) through (c) are for a 16-row planter used in 2022, and plots (d) through (f) are for a 24-row planter used in 2023. Each plot includes a fitted model that quantifies the relationship between predictors and the respective response variables: bias (Y_b), precision (Y_p) and accuracy (Y_a).

Figures 3(b) and (e), the response surfaces for the precision of 16-RP and 24-RP exhibit saddle points within the experimental region. A trend of poor precision with increasing planting speed is evident. For the 16-RP, a downforce of 209 lbf with a planter speed of 7.4 mph results in a local minimum. Likewise, 231 lbf downforce with a speed of 6.6 mph yields a local minimum for the 24-RP.

Figure 3(c) for the 16-RP and Figure 3(f) for the 24-RP indicate that accuracy follows a trend analogous to bias. Increased speed decreases accuracy, with a discernable shift beyond the 8 mph threshold, and increased downforce initially improves accuracy at lower speeds but has a diminishing effect as speeds escalate. The optimal factor levels for achieving maximum accuracy are 299 lbf at 7.9 mph for the 16-RP and 165 lbf at 4.8 mph for the 24-RP.

Despite being termed as minimas in a mathematical sense (refer to Eq. (2) and Eq. (3)), it is important to note that the optimal factor levels for both precision and accuracy correspond to the highest values achievable and are interpreted accordingly.

Track Section

Subsequent analysis of the track section and the contour plots in Figure 4(a) and Figure 4(d) indicates that the optimal downforce and speed settings for the 16-RP are 146 lbf and 6.8 mph, respectively, and the associated bias is 0.17 in. Operating the planter within a downforce range of 128 to 164 lbf and a speed range of 6.1 to 7.5 mph achieves a seeding depth consistently between 1.81 and 2.18 in. Beyond these moderate settings, noticeably after 9 mph, bias deteriorates regardless of the applied downforce levels. The model explains 77 % of the variability present in bias. In parallel, the 24-RP shows a minimum bias of 0.22 at 237 lbf downforce and 5.4 mph planter speed. A consistent speed of 5.4 mph and a downforce within the range of 237 to 259 lbf ensures seeding depth within 1.78 to 2.21 in. The model accounts for 38 % of the variability observed on the bias.

While 24-RP exhibits higher bias levels overall, its ascent in bias with the increase in planting speed at higher downforce settings is less steep than when contrasted with 16-RP. It

implies that the track section of 24-RP may provide a slight advantage in seeding depth consistency, particularly at higher downforce levels.

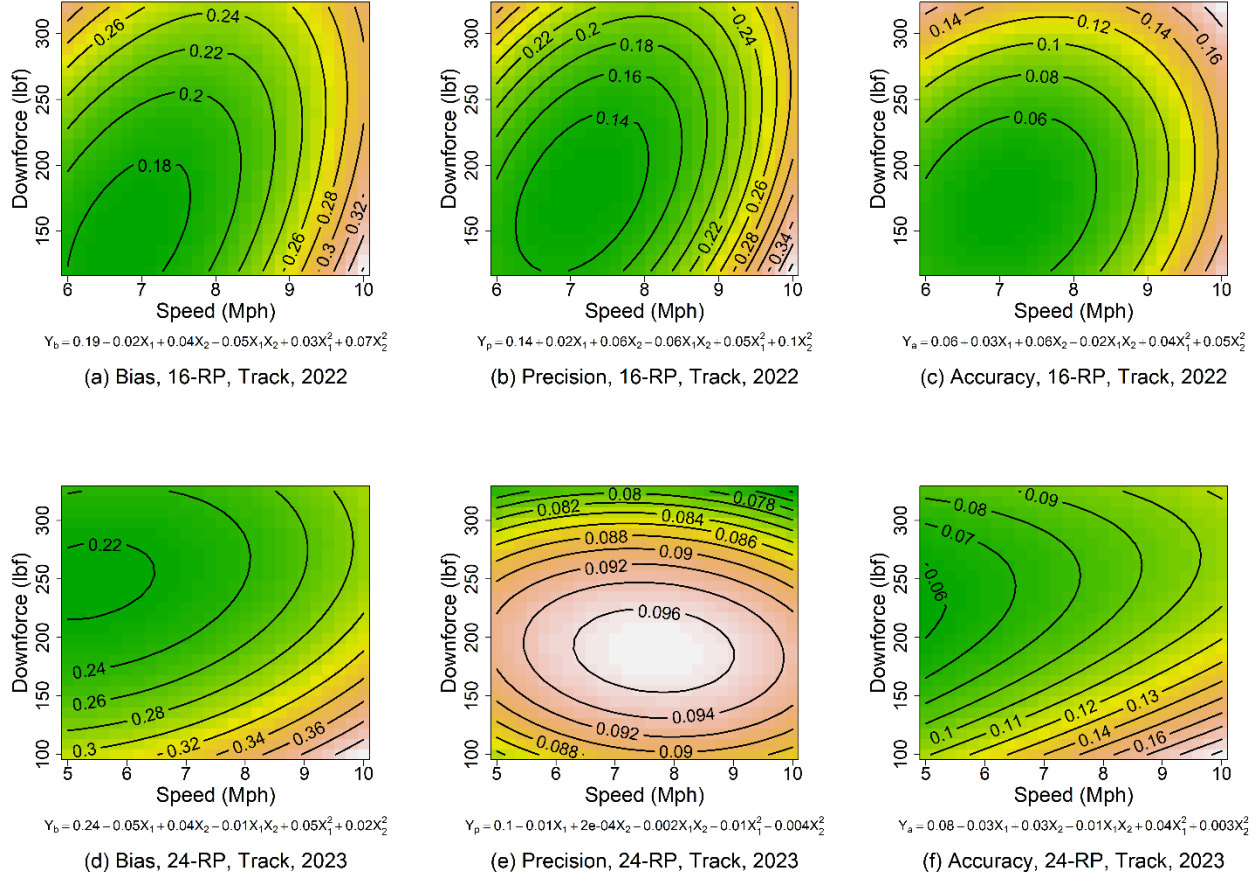


Figure 2. 4 Contour plots to illustrate the combined effects of downforce (lbf) settings and planting speed (mph) on bias, precision, and accuracy of seeding depth for the track section of the planter. Plots (a) through (c) are for a 16-row planter used in 2022, and plots (d) through (f) are for a 24-row planter used in 2023. Each plot includes a fitted model that quantifies the relationship between predictors and the respective response variables: bias (Y_b), precision (Y_p) and accuracy (Y_a).

The highest precision for the 16-RP is centrally located at a downforce of 179 lbf and a planter speed of 7.1 mph, as shown in Figure 4(b). Contrary to expectations, Figure 4(e) indicates that 24-RP exhibits poor precision values at moderate downforce and speed. Improvement in precision is contingent on operating the 24-RP at downforce levels of 300 lbf and higher.

For accuracy, the quadratic model's contour plots are presented in Figures 4(c) and 4(f). Figure 4(c) shows the maximum accuracy for the 16-RP when operated at 168 lbf and with 7.0 mph planter speed. Similarly, accuracy for the 24-RP peaks at 262 lbf downforce and a planting speed of 7.3 mph. For the 16-RP, precision suffers at planting speeds beyond 9 mph and a combination of low speeds and high downforce. 24-RP appears capable of maintaining better accuracies even with higher planting speeds, provided it is operated at downforce levels at or above 200 lbf.

Wing Section

Extending the analysis to the wing section reveals that the ideal operational settings for downforce and speed on the 16-RP are 222 lbf and 7.1 mph, with a resulting bias of 0.2 in. When the planter operates within a downforce range of 217 to 227 lbf and at planting speeds within 6.5 to 7.7 mph, it consistently plants seeds between 1.8 to 2.2 in. Beyond a planting speed of 8.5 mph, a minor increase in planting speed results in a steep escalation of bias, as evidenced by narrowly arrayed contour lines in Figure 5 (a). Minimal change in bias is observed in the region regardless of increases in downforce. The model explains 46 % of the variability inherent in bias. Simultaneously, a local minimum for bias was observed for the 24-RP at 224 lbf downforce and 7.3 mph planting speed. Figure 5 (e) shows that the bias values are less desirable at both low and high extremes of downforce, and bias is optimized within a moderate downforce range.

Figure 5(b) shows that the surface for the precision of the 16-RP is a saddle point with maximum precision obtained at 80 lbf downforce and a planter speed of 6.9 mph. Regions of higher downforce and speed—beyond 250 lbf and 8 mph, exhibit poor precisions. 200 lbf

downforce and 6.7 mph planting speed yield the highest precision for 24-RP, as evident in Figure 5(e). However, the model exhibits a significant lack of fit ($p < 0.05$).

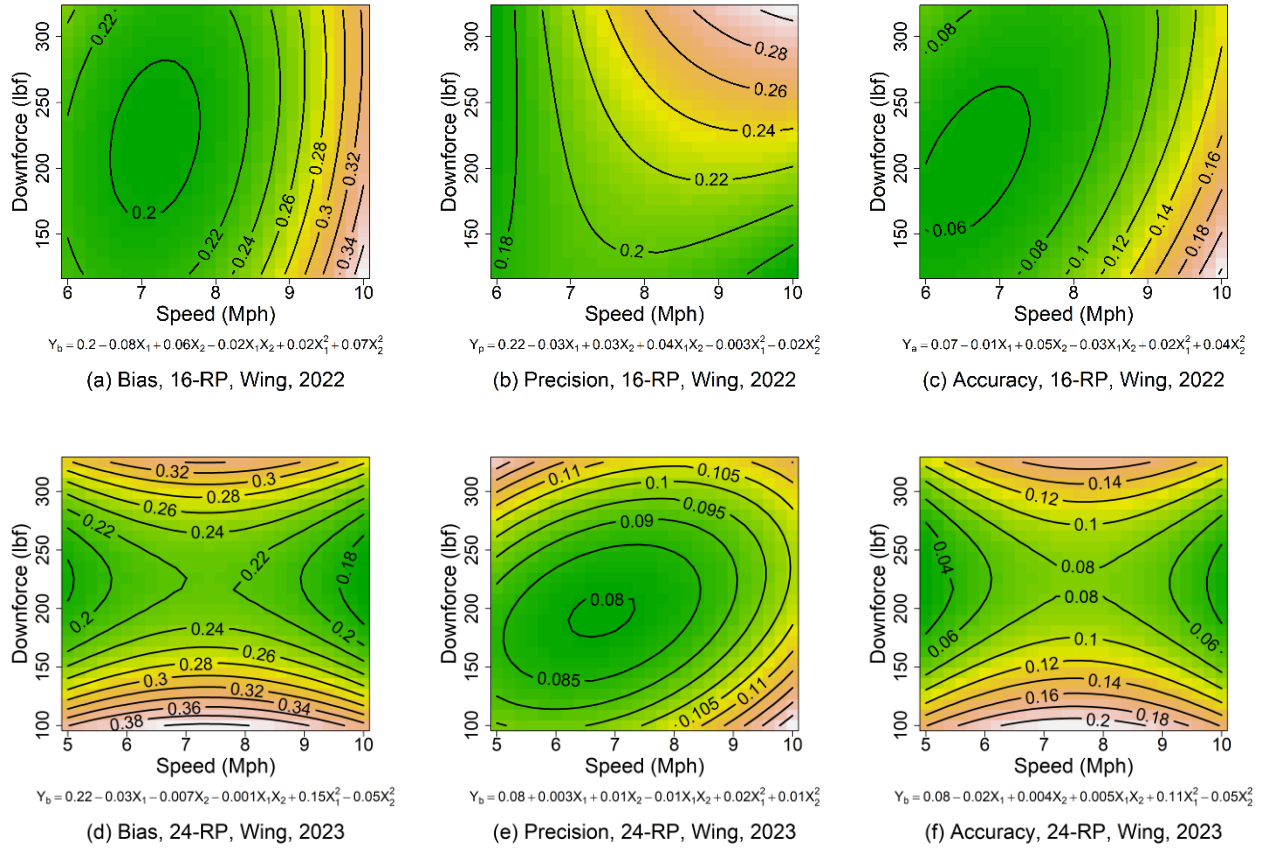


Figure 2. 5 Contour plots to illustrate the combined effects of downforce (lbf) settings and planting speed (mph) on bias, precision, and accuracy of seeding depth for the wing section of the planter. Plots (a) through (c) are for a 16-row planter used in 2022, and plots (d) through (f) are for a 24-row planter used in 2023. Each plot includes a fitted model that quantifies the relationship between predictors and the respective response variables: bias (Y_b), precision (Y_p) and accuracy (Y_a).

Accuracy is optimized at a downforce of 205 lbf and a planting speed of 6.6 mph for the 16-RP, as shown in Figure 5(c). Comparable to bias, accuracy suffers at higher planting speeds, notably beyond 9 mph. Figure 5 (f) indicates that the accuracy surface for the 24-RP is also a saddle. The local maximum was observed at 223 lbf downforce and 7.61 mph planting speed, and moderate downforce values—175 lbf to 275 lbf, are desirable for better accuracies.

Table 2. 8 ANOVA results of the response surface model for three responses: bias, precision, and accuracy across three rows for the experimental year 2022

Source	Bias				Precision				Accuracy				
	SS	MS	F-value	$p > F$	SS	MS	F-value	$p > F$	SS	MS	F-value	$p > F$	
Non-Track (N)													
$FO(X_1, X_2)$	0.019	0.010	1.701	0.273	0.006	0.003	0.821	0.492	0.008	0.004	3.211	0.127	
$TWI(X_1, X_2)$	0.002	0.002	0.300	0.607	0.004	0.004	1.070	0.348	0.003	0.003	2.087	0.208	
$PQ(X_1, X_2)$	0.023	0.011	1.981	0.232	0.004	0.002	0.486	0.642	0.008	0.004	3.297	0.122	
Residual	0.029	0.006			0.019	0.004			0.006	0.001			
Lack of fit	0.016	0.005	0.890	0.568	0.006	0.002	0.310	0.821	0.005	0.002	2.791	0.275	
Pure error	0.012	0.006			0.013	0.007			0.001	0.001			
$R^2 = 0.61$					$R^2 = 0.42$					$R^2 = 0.75$			
Track Section (T)													
$FO(X_1, X_2)$	0.020	0.010	3.768	0.101	0.031	0.016	7.419	0.032	0.017	0.009	23.782	0.003	
$TWI(X_1, X_2)$	0.009	0.009	3.378	0.126	0.015	0.015	6.948	0.046	0.002	0.002	5.870	0.060	
$PQ(X_1, X_2)$	0.016	0.008	3.028	0.138	0.035	0.018	8.311	0.026	0.013	0.007	17.974	0.005	
Residual	0.013	0.003			0.011	0.002			0.002	0.000			
Lack of fit	0.001	0.000	0.041	0.986	0.008	0.003	2.374	0.310	0.000	0.000	0.045	0.984	
Pure error	0.013	0.006			0.002	0.001			0.002	0.001			
$R^2 = 0.77$					$R^2 = 0.88$					$R^2 = 0.95$			
Wing (W)													
$FO(X_1, X_2)$	0.025	0.013	1.410	0.327	0.010	0.005	1.357	0.338	0.019	0.010	3.328	0.121	
$TWI(X_1, X_2)$	0.001	0.001	0.127	0.736	0.006	0.006	1.607	0.261	0.003	0.003	1.175	0.328	
$PQ(X_1, X_2)$	0.013	0.007	0.732	0.526	0.001	0.001	0.160	0.857	0.006	0.003	0.958	0.445	
Residual	0.045	0.009			0.019	0.004			0.014	0.003			
Lack of fit	0.027	0.009	0.958	0.547	0.007	0.002	0.371	0.787	0.011	0.004	1.957	0.356	
Pure error	0.018	0.009			0.012	0.006			0.004	0.002			
$R^2 = 0.46$					$R^2 = 0.48$					$R^2 = 0.66$			

SS: sum of squares; MS: mean square; FO: first order linear model; TWI: two-way interaction; PQ: pure quadratic

Table 2. 9 ANOVA results of the response surface model for three responses: bias, precision, and accuracy across three rows for the experimental year 2023

Source	Bias				Precision				Accuracy			
	SS	MS	F-value	$p > F$	SS	MS	F-value	$p > F$	SS	MS	F-value	$p > F$
Non-Track (N)												
$FO(X_1, X_2)$	0.048	0.024	2.791	0.154	0.005	0.003	2.983	0.140	0.013	0.007	2.039	0.225
$TWI(X_1, X_2)$	0.032	0.032	3.755	0.110	0.007	0.007	7.884	0.038	0.040	0.040	12.340	0.017
$PQ(X_1, X_2)$	0.057	0.029	3.331	0.120	0.007	0.003	3.720	0.102	0.041	0.020	6.315	0.043
Residual	0.043	0.009			0.005	0.001			0.016	0.003		
Lack of fit	0.018	0.006	0.472	0.733	0.001	0.000	0.268	0.846	0.011	0.004	1.385	0.445
Pure error	0.025	0.013			0.003	0.002			0.005	0.003		
	$R^2 = 0.76$				$R^2 = 0.80$				$R^2 = 0.85$			
Track Section (T)												
$FO(X_1, X_2)$	0.023	0.011	0.943	0.449	0.000	0.000	0.122	0.888	0.009	0.004	0.957	0.445
$TWI(X_1, X_2)$	0.001	0.001	0.102	0.763	0.000	0.000	0.163	0.703	0.001	0.001	0.202	0.672
$PQ(X_1, X_2)$	0.013	0.007	0.551	0.608	0.000	0.000	0.274	0.771	0.005	0.003	0.577	0.595
Residual	0.060	0.012			0.003	0.001			0.022	0.004		
Lack of fit	0.053	0.018	5.170	0.166	0.002	0.001	1.694	0.392	0.021	0.007	16.474	0.058
Pure error	0.007	0.003			0.001	0.000			0.001	0.000		
	$R^2 = 0.38$				$R^2 = 0.16$				$R^2 = 0.40$			
Wing (W)												
$FO(X_1, X_2)$	0.006	0.003	0.190	0.833	0.000	0.000	0.101	0.906	0.003	0.001	0.290	0.760
$TWI(X_1, X_2)$	0.000	0.000	0.002	0.971	0.000	0.000	0.371	0.569	0.000	0.000	0.044	0.842
$PQ(X_1, X_2)$	0.053	0.026	1.601	0.290	0.002	0.001	0.936	0.452	0.030	0.015	2.944	0.143
Residual	0.083	0.017			0.005	0.001			0.026	0.005		
Lack of fit	0.022	0.007	0.249	0.858	0.005	0.002	53.193	0.019	0.011	0.004	0.469	0.734
Pure error	0.060	0.030			0.000	0.000			0.015	0.008		
	$R^2 = 0.42$				$R^2 = 0.33$				$R^2 = 0.56$			

SS: sum of squares; MS: mean square; FO: first order linear model; TWI: two-way interaction; PQ: pure quadratic

Optimizing Multiple Responses Under Constraints

The optimal parameters (Table 2.10 and Table 2.11) obtained for each section of the planter, obtained by building a response surface methodology, were considered simultaneously to find a set of operation conditions that kept the bias of seeding depth within a desired 0.25 in.

Table 2. 10 Optimal downforce (lbf) and speed (mph) for 16 Row planter

16-RP Planter / Experimental Year 2022						
Section	Bias		Precision		Accuracy	
	Downforce	Speed	Downforce	Speed	Downforce	Speed
Non-Track	222	7.5	209	7.4	299	7.9
Track	146	6.8	179	7.1	168	7.05
Wing	222	7.1	80	6.9	205	6.6

Table 2. 11 Optimal downforce (lbf) and speed (mph) for 24 Row planter

24-RP / Experimental Year 2023						
Section	Bias		Precision		Accuracy	
	Downforce	Speed	Downforce	Speed	Downforce	Speed
Non-Track	232	7.3	231	6.6	165	4.8
Track	237	5.4	189	7.6	262	7.3
Wing	224	7.3	200	6.7	223	7.61

For 16-RP, compared to the non-track section, which requires a downforce of 222 lbf for optimal bias performance, the track section's highest downforce requirement is lower by 52.05 %. In contrast, the Wing section's downforce requirement for bias is nearly identical to the Non-track, with a minuscule difference of just 0.045 %. These findings indicate significant variability in downforce needs across the sections of 16-RP for bias optimization. The Non-track and Wing sections have nearly equivalent requirements, contrasting with the substantially lower requirement in the track section.

Similarly, for 24-RP, the track section requires the highest downforce—237 lbf for optimal performance, 2.15 % more than the non-track section. The wing section requires 5.80 % less downforce than the track section. While there are differences in downforce requirements among the sections for bias optimization, they are relatively minor, especially when comparing the non-track and track sections. The wing section does show a slightly larger difference but still within a narrow range.

Conclusion

The following conclusions are drawn from the study:

- Increased downforce consistently leads to deeper average seeding depths across both experimental years, indicating that higher downforce settings are effective for achieving greater seeding depths. The variability in seeding depths also increased with increasing downforce.
- Higher planting speeds slightly reduce the average seeding depth and impact the consistency of seeding depths, with lower speeds tending to produce more uniform results. This effect was seen in both 2022 (planted with 16-RP) and 2023 (planted with 24-RP).
- Analysis reveals distinct downforce requirements among sections of both 16-RP and 24-RP, with differences slightly more pronounced in the 16-RP. The Track section benefits from lower speeds to minimize bias in both planters

Chapter 3 - Assessing Corn Spacing Inequality and Yield Disparities

Using Lorenz Curves and the Gini Index

Introduction

Plant spacing can be defined as the distance maintained between individual crops within a row. Uniform plant-to-plant spacing within a row is one of the most important factors that govern the success of crop establishment for corn (*Zea Mays L.*) plants (Brilhador et al., 2015; Carreira et al., 2022). A uniform distribution of in-row plant spacing is essential as it significantly influences how individual plants interact with adjacent plants for abiotic and biotic resources. It minimizes competitive stress within the plant community, improves the efficacy of resource use, and increases instances of successful pollination, collectively promoting vigorous crop growth and optimizing yields (Karayel & Šarauskis, 2011; Sangoi et al., 2002; Zhang et al., 2014). The within-row spacing of corn plants is a function of seed density. For rows spaced 26—36 in. apart, adjusting the plant spacing between 7—8.5 in. maximizes the ear size, thereby optimizing yield potential (Drost & Alston, 2021; J. Lauer, 2002; Wood, 2023).

Plant spacing variability (PSV), defined as the standard deviation of consecutive plant-to-plant spacing within a row (B. Nielsen, 1995), is affected by the planter and its operational settings, among other factors (Dufour, 2021). A planter's ability to precisely meter seeds, ensuring singulation and uniform delivery through the seed tube into the furrow, regulates the uniformity in plant spacing. Uniformity in plant spacing evaluates machine performance and demonstrates its efficiency. Skips and doubles can result from poorly calibrated equipment and suboptimal agronomic practices. (Carreira et al., 2022; J. G. Lauer & Rankin, 2004; M. F. Kocher et al., 2011). Skips contribute most to yield losses by spacing irregularities; studies have shown that 12—36-in. gaps can reduce the yield by 2 % compared to a uniform stand. Yield reduction increases with

frequent and wider gaps; a 5—6 % yield loss is expected if the gap widens to 4—6 ft (Ben Rosser, 2021).

Precision planters are designed to efficiently singulate seeds at the correct ratio, but inadequate planter maintenance and high operating speeds often contribute to substandard within-row spacing uniformity. Planting at high speeds induces vibration in seed meters, affecting the singulation process and increasing the variability in seed spacing (Ben Rosser, 2021; Quanwei et al., 2017). Staggenborg et al. (2004) experimented on corn over two years, with planting speeds ranging from 4—9 mph, and reported a change of 0.20—0.32 in. in PSV for every mile increase in planting speed. Similar on-farm trials in the Midwest region of the United States, within a speed range of 4—7 mph, reported a rise in PSV by 3.9—5.7 in. per mile increase in planting speed (B. Nielsen, 1995). Badua et al. (2021) reported significant differences in plant spacing across ground speeds varying from 5—10 mph. An increase in ground speeds resulted in wider plant spacing with higher variability. The decline in spacing uniformity can be traced back to the seed flow disruptions within the seed tube, attributed to excessive vibration of the row units at higher planting speeds. Even though operating the planter at low downforce settings resulted in lower spacing variability, researchers reported no significant effect of downforce on plant spacing.

Corn yields are sensitive to spatial and temporal variations. Studies identify uniform emergence and consistent plant spacing as two of the most crucial factors influencing yield, among several others—non-ideal emergence and plant spacing typically result in lower grain yields (Doerge et al., 2015; Dufour, 2021). Multiple studies report penalized yield with increasing PSV. A significant yield loss of 160 kg ha⁻¹ was observed for every inch increase in PSV beyond a threshold of 2 in. (Doerge et al., 2015; Nafziger, 2009; B. Nielsen, 1995). Studies in Kansas on plant spacing concluded that non-uniform plant-to-plant spacing correlates with lower grain yields.

Follow-up studies reported a positive yield response with increasingly similar spacing among within-row plants (Thompson, 2014). The impact of plant spacing variability on corn yield is a subject of contention across various studies, with other research concluding that it has a small or non-significant effect on corn yield. (J. G. Lauer & Rankin, 2004; W. Liu et al., 2004b). The inconsistent effect of PSV on yield could also result from plant density differences (Thompson, 2014).

Commonly used descriptors of plant-to-plant spatial variability include moments around the mean, i.e., standard deviation, skewness, and kurtosis (Sadras & Bongiovanni, 2004). Such traditional metrics might not comprehensively reflect the spacing variabilities of actual field conditions. Characterizing plant spacing only by the mean distance between adjacent plants overlooks spatial patterns such as skips or clusters, potentially leading to misleading conclusions about stand uniformity and its effect on yield. Outliers significantly influence the standard deviation (SD) and the coefficient of variation (CV), limiting their ability to accurately identify specific spatial patterns, such as doubles, clusters, skips, or combinations (Andrade et al., 2005; Masino et al., 2018; Pereyra et al., 2022). The inadequacies of traditional descriptors highlight the need for a new method to evaluate plant-to-plant spacing variability that accurately captures the spatial distribution and quantifies the inequality within plants.

Jacob Weiner et al. (1984) suggested using Lorenz curves and the Gini coefficient—a method developed by economists to assess wealth inequality within a population and allows for comparisons among populations. The Lorenz curve is a graphical presentation of population distribution, whereas the Gini coefficient quantifies the inequality that distribution represents. The technique finds its use beyond economics and statistics in various disciplines like genetics, astrophysics, and digital imaging; however, its use in agronomy and agricultural applications is

not as common (Haye & Zizler, 2021; Sitthiyot & Holasut, 2021). Sadras & Bongiovanni (2004) analyzed the variation in corn grain yield in Argentina at the paddock scale using Lorenz curves and Gini coefficients. The study concluded that these methods are reliable tools for assessing crop heterogeneity in terms of inequality.

Building on this premise, we hypothesize that a row crop planter's planting speed and applied downforce influence the uniformity of within-row plant spacing, leading to measurable inequalities in grain yield. This study aims to quantify these effects with the following objectives: (i) assess plant-to-plant spacing inequality for different combinations of planting speed and applied downforce using Lorenz curves and the Gini index, (ii) explore whether plant-to-plant spacing inequality correlates with grain yield at plant level, (iii) establish a relationship between spacing inequality—as quantified by Gini index—and yield per plant employing regression analysis techniques.

Materials and Methods

Site Description and Field Experiments

Two field experiments were conducted in Kansas, United States; the first (Exp. 1) in 2022, followed by a second (Exp. 2) in the subsequent growing season in 2023. The plot for Exp. 1 (39°18'11.0"N, 97°10'29.8"W) has a Crete Clay Loam texture, displays hillslope toposequence, and is 1300 ft above sea level. Similarly, the plot for Exp. 2 (39°20'56.4"N, 97°10'44.7"W) is characterized by Crete Silt Loam texture, exhibits interfluvial landscape, and is 1020 ft above sea level. Standard farming norms followed by local farmers and no-tillage farming practices were adopted in both fields.

Corn was planted with a 16-row JD 1775NT16Row30 ExactEmerge™ (Deere & Company, Moline, IL) at 22000 seeds/acre seeding rate, with a target spacing of 9.45 in. on May 12, 2022, for Exp. 1. Exp. 2 was sown with a 24-row JD 1775NT 24Row30 ExactEmerge™ (Deere & Company, Moline, IL) at a seeding rate of 27400 seeds/acre, with a target spacing of 7.60 in. on April 24, 2023. Experimental strips were 17.5 ft long, spaced 30 in. apart, and planted at a target depth of 2 in. for both experiments. Both planters feature a BrushBelt™ seed delivery mechanism.

Study Design and Data Collection

Studies were arranged in a split-plot randomized complete block fashion (Montgomery, 2013), with three replications of each treatment combination for both Exp. 1 and Exp. 2. For both designs, downforce was the whole-plot factor, with planting speed nested within as a sub-plot factor. In 2022, three levels of downforce settings were selected—120, 220, and 320 lbf, and three levels of planting speed—6, 7.5, and 10 mph. Likewise, in 2023, four levels of downforce—100, 175, 250, and 325, and three levels of planting speed—5, 7.5, and 10 mph were assigned. For analysis speed levels were categorized as low (5, 6 mph), moderate (7.5 mph), and high (10 mph). Similarly, downforce levels were categorized as low (100, 120 lbf), moderate (175, 220, 250 lbf) and high (320, 325 lbf).

All plant spacing measurements were taken post-emergence at the V3 stage when seedlings were easy to identify. The distance between successive plants was measured using a POGO stick (Precision Planting, Tremont, IL) for Exp. 1 and by laying down a standard tape measure (Leverlock, Stanley Black and Decker, New Britain, CT) along the strip for Exp. 2 (ISO 7256, 1984). PSV—the SD between consecutive plant-to-plant spacings (Brilhador et al., 2015) and CV, both indicators of spacing uniformity, were determined using Eq. (1) and Eq. (2).

$$SD_i = \sqrt{\frac{1}{n_i - 1} \sum_{j=1}^n (s_{ij} - \bar{s}_i)^2}, \quad (9)$$

$$CV_i = \frac{SD_i}{\bar{s}_i}, \quad (10)$$

where $i = 1, 2, 3 \dots$, is the treatment strip sampled, n_i is the total number of samples in the strip, s_{ij} is the j^{th} measurement from the i^{th} strip, and $\bar{s}_i$ is the average plant spacing of that strip.

Individual ears were hand-harvested from each experimental strip and shelled (Maizer SES, Almaco, Nevada, IA) to obtain yield per plant. The moisture-adjusted yield for each plant was derived by correcting the kernel weights of each ear to a standard 15.5 % moisture content.

Other indicators of spacing uniformity evaluated in the study include multiples (D), miss index (M), quality of feed index (A), and precision index (C). These indices are based on theoretical spacing for a planter as defined by the International Organization for Standardization (1984). These metrics are calculated by dividing plant spacing observations into different regions with reference to the theoretical spacing (X_{ref}) as shown in Figure 3.1, using the following formulas:

$$D = \frac{n_I}{N}, \quad (11)$$

where n_I is the number of spacing observations less than or equal to half of X_{ref} and N is the total number of spacing measurements taken.

$$M = \frac{n_{III} + n_{IV} + n_V}{N}, \quad (12)$$

where n_{III} , n_{IV} , and n_V are observations greater than $1.5 X_{ref}$. Single skips include only n_{III} observations.

$$A = \frac{n_{II}}{N}, \quad (13)$$

where n_{II} are observations between $1.5 X_{ref}$ to $2.5 X_{ref}$.

$$C = \frac{SD_{n_{II}}}{X_{ref}}, \quad (14)$$

where $SD_{n_{II}}$ is the standard deviation of singles.

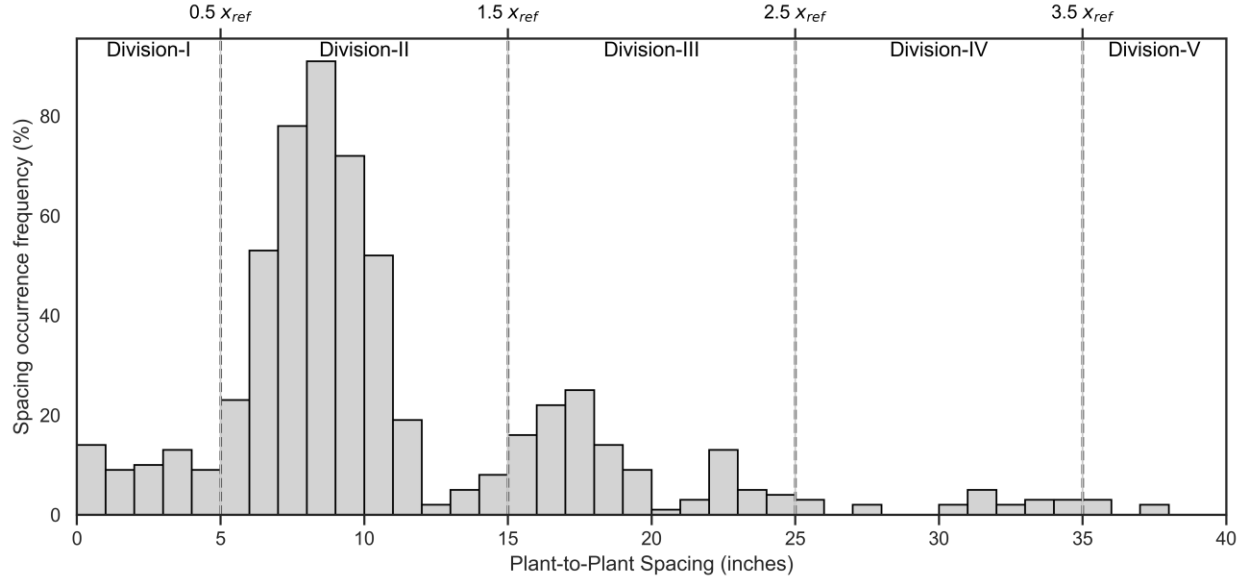


Figure 3. 1 Five divisions used to obtain spacing uniformity metrics—multiples, miss, quality of feed, and precision with reference to theoretical spacing. A theoretical spacing of 10 in. was used for illustration purposes.

Lorenz Curve and Gini Index

The Lorenz curve is a graphical measure of inequality within a population. It is one of the several approaches developed in the economics literature and used in studying inequality among plant populations (Lorenz, 1905; Weiner et al., 1984). Plant-to-plant spacings in each treatment combination are ranked in ascending order to construct Lorenz curves. The cumulative proportion of the plant population (x-axis) is plotted against the cumulative proportion of spacing (y-axis). A $y = x$ line indicates perfect equality, deviations from this line represents Lorenz curve, and it can be expressed as Eq. (7) (Damgaard & Weiner, 2000; Torres, 2012).

$$L(y) = \int_0^y s dF(s)/\mu, \quad (15)$$

where $L(y)$ represents the Lorenz curve, $F(s)$ is the cumulative distribution function of ordered plant spacings, and μ is average plant spacing.

The Gini index (G) quantifies the extent of inequality by calculating the area ratio between the Lorenz curve and the line of perfect equality, with the entire area beneath the line of equality. It ranges from zero—when all plants are equally spaced, to a theoretical maximum of 1—when all but one plant are clustered together (Sadras & Bongiovanni, 2004). The Gini index was estimated using Eq. (8) and subsequently multiplied by $n/(n - 1)$ to obtain its unbiased estimates (Sen & Foster, 1973; Torres, 2012).

$$G = \frac{\sum_{i=1}^n \sum_{j=1}^n |s_i - s_j|}{2n^2\mu}, \quad (16)$$

where n is the sample size, s_i and s_j are plant spacing of the i^{th} and j^{th} plant, respectively. μ is the average plant spacing for the treatment group.

The analysis of plant-to-plant yield was performed with the same rationale. A total of 1701 observations for Exp. 1 and 3240 observations for Exp. 2 were used to obtain the indexes.

The relationship between spacing inequality—expressed as the Gini index, and yield per plant was quantified using regression techniques.

Results

Operation Settings and Effects on Spacing Uniformity

In both experiments, the actual plant-to-plant spacing exceeded the theoretical expectations; Exp. 1 achieved an average spacing of 8.10 in. with a PSV of 2.10 in., while Exp. 2 observed an average of 10.51 in. with a PSV of 3.95 in. The effect of planter speed and applied downforce was significant ($\alpha = 0.10$) for four out of six uniformity metrics evaluated (Table 3.1).

Specifically, the precision index (Figure 3.2) was significantly affected by changes in planter speed; it increased by 10 % as planter speed transitioned from lower to moderate levels and by 14 % as speed levels reached high. Relatively similar values of the precision index were observed between low and moderate levels of downforce; however, a significant increase of 9 % was observed at high levels of downforce. A noticeable increase in multiple occurrences was seen as the planter transitioned from low to moderate speeds. However, multiples decreased marginally upon further increase from moderate to high levels, remaining relatively comparable across both levels. Other spacing uniformity metrics—namely PSV, miss, quality, and Gini index of spacing (G-spacing) deteriorated with increasing speed levels. While quality improved by 3 % as downforce levels were raised from low to high, PSV, miss, multiples, precision, and G-spacing failed to exhibit a consistent trend.

The combination of applied downforce and planter speed influenced variability in plant-to-plant spacing for both experiments, as demonstrated by the overall G-spacing range (0.097—0.187). In 55 % of cases (10 out of 18), increased speed corresponded with a higher G-spacing. Further analysis reveals an increase rate of 60 % when operating at both low and high downforce levels, while a slightly lower increase rate of 50 % was observed at moderate downforce levels. The trend indicates that planter speed is an important factor in precision planting and needs prudent management to optimize plant-to-plant spacing distribution.

The Lorenz curves effectively illustrate the inequality in plant-to-plant spacing among different treatment combinations, and the Gini coefficient quantifies the degree of inequality present in the distribution. For Exp. 2, as illustrated in Figure 3.3(a), operational settings of high speed combined with low downforce resulted in higher G-spacing (0.136). A relatively higher G-yield (0.258) was also associated with these settings. In contrast, operating the planter at low speed

and moderate downforce resulted in minimal spacing inequality, as reflected by a lower G-spacing of 0.097. Similarly, this configuration also exhibited a lower G-yield (0.156), indicating less inequality in yield distribution. Figure 3.3(b) and (c) present the frequency distributions of plant-to-plant spacing along with key descriptive metrics for the two operational configurations, respectively. An average plant-to-plant spacing of 7.98 in. was achieved at low speed and moderate downforce settings. In contrast, high speed and low downforce resulted in a slightly higher average of 8.43 in. Comparatively lower variability (SD = 1.73 inches) and relative dispersion (CV = 21.70 %) associated with low speed and moderate downforce settings suggest greater consistency in plant spacing.

Table 3. 1 Analysis of variance and treatment means for the effect of planter speed and applied downforce on different uniformity metrics—PSV, miss, doubles, quality, precision, and G-spacing.

Factor	PSV (inches)	Spacing CV	Miss (%)	Single skips (%)	Double skips (%)	Multiple (%)	Quality (%)	Precision	G spacing
Speed									
Low	2.84	0.293	7.33	6.52 a	0.654	1.54	91.1	0.134 a	0.138
Moderate	2.85	0.293	8.34	7.75 ab	0.503	1.84	89.8	0.148 b	0.148
High	2.87	0.292	9.34	8.74 b	0.578	1.76	88.9	0.153 b	0.149
p-value	0.981	0.996	0.187	0.103	0.866	0.723	0.156	0.003	0.121
Downforce									
Low	3.01	0.309	9.8 a	9.05	0.678	1.81 ab	88.4	0.143 ab	0.152
Moderate	2.76	0.286	7.37 b	7.00	0.278	2.09 b	90.5	0.140 a	0.140
High	2.80	0.283	7.84 ab	6.97	0.780	1.24 a	90.9	0.152 b	0.143
p-value	0.396	0.320	0.075	0.095	0.158	0.093	0.090	0.100	0.136

Note: Means followed by different grouping alphabets indicate statistically significant differences at $\alpha=0.1$.

In Exp. 1, lower G-spacing (0.162) was observed again for low speed and moderate downforce settings, as demonstrated in Figure 3.4(g). It was also paralleled by a lower G-yield (0.155). On the other end, operating the planter at high speed and low downforce results in an observable increase of G-spacing (0.183) coupled with a higher G-yield (0.186). The increase in both metrics indicates greater inequality in spacing and yield. Frequency distribution in Figure 3.4(h) and (i) shows an average plant-to-plant spacing of 10.3 in. (SD = 3.90 in., CV = 37.83 %)

for low speed and moderate downforce settings, whereas, for high speed and low downforce, it is 11.14 in. (SD = 4.07 in., CV = 36.54 %). At low speed and moderate downforce, spacing distribution is leptokurtic ($K = 16.04$), with heavy tails indicating the presence of occasional extreme deviations from average behavior. The Lorenz curve in Figure 3.4(g) captures this trend as an inflection at about 85 % of the cumulative population. The inflection indicates that about 15 % of the plant population occupies significantly wider spacing than the majority.

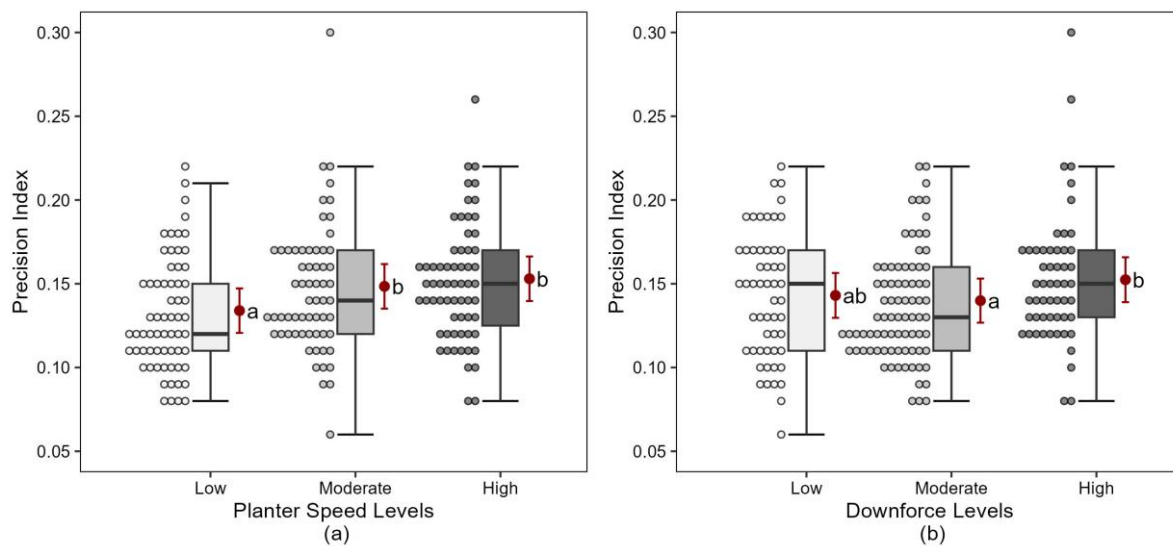


Figure 3. 2 Variation in precision index across different planter speeds (a) and downforce levels (b). Boxplots demonstrate the distribution of the precision index; error bars to their right show the estimated mean and the standard error associated with the estimation. Treatment means followed by different grouping alphabet indicate statistically significant differences at $\alpha=0$.

In addition to these specific findings within each experiment, it is notable that G-spacings were consistently higher in Exp. 1 than in Exp. 2. The difference may suggest that plant density and environmental factors may contribute to inequality in addition to operational settings.

Spacing Uniformity and Effects on Yield

The analysis of the effects of plant spacing on corn yield outcomes reveals a significant correlation ($r = -0.58$, $p < 0.001$) between the choice of theoretical spacing and yield per plant. The average yield per plant at a target spacing of 7.60 in. was 179.8 g, with an overall yield range

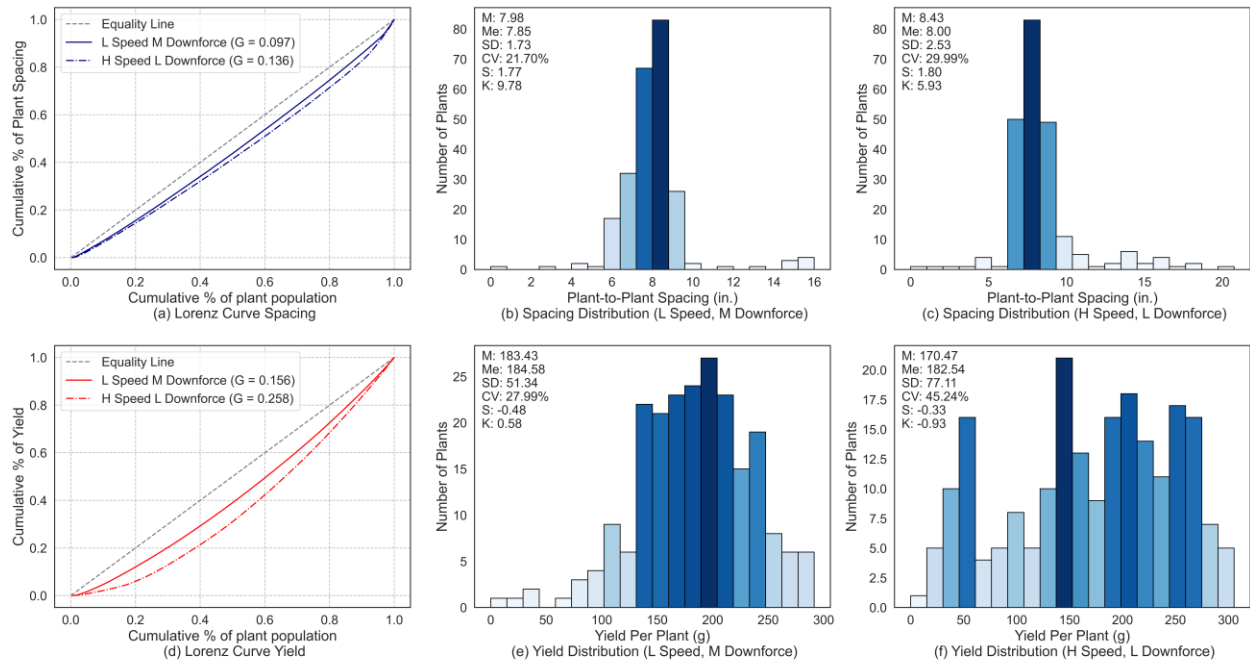


Figure 3.3 Comparative Lorenz curves and histograms for plant-to-plant spacing and yield per plant for Exp-1. (g) Lorenz curve for plant-to-plant spacing; the straight line represents absolute equality in plant population. Histograms (h) and (i) show spacing distributions for treatment combinations. (j) Lorenz curves for yield per plant. Histograms (k) and (l) illustrate the distribution of yield per plant for respective treatments.

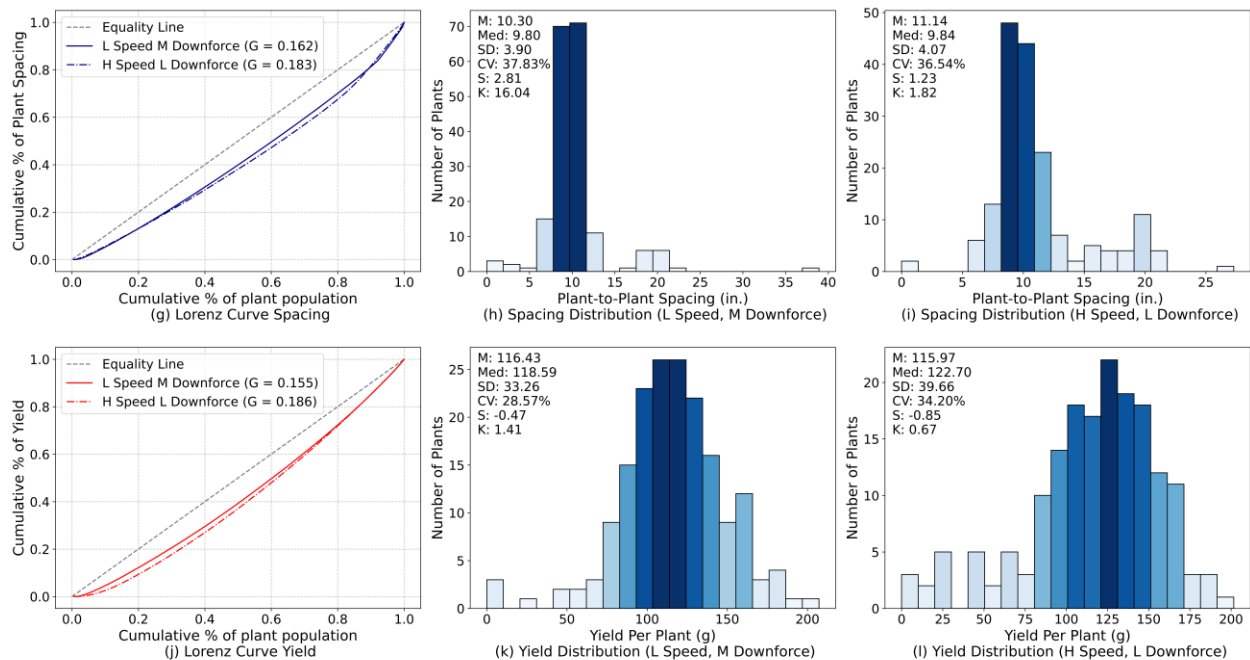


Figure 3.4 Comparative Lorenz curves and histograms for plant-to-plant spacing and yield per plant for Exp-1. (g) Lorenz curve for plant-to-plant spacing; the straight line represents absolute equality in plant population. Histograms (h) and (i) show spacing distributions for treatment combinations. (j) Lorenz curves for yield per plant. Histograms (k) and (l) illustrate the distribution of yield per plant for respective treatments.

between 44.4 and 262.9 g. Moreover, 50 % of the yield per plant is concentrated within a narrow range between 151.8 to 212.6 g. In comparison, a wider target spacing of 9.45 in. resulted in an average yield per plant of 128.4 g, the range spanning from 91.9 to 190.7 g. Again, half of the yield data lies within a range between 116.5 to 138.2 g. A regression analysis that followed supports the hypothesis that theoretical spacing significantly influences ($\beta = -50.6, p < 0.001$) yield outcomes for each plant. Subsequent pairwise comparisons using Tukey adjustments—shown in Figure 3.5(a)—corroborate that the difference in yield outcomes between the two theoretical spacings is statistically significant ($\alpha = 0.05$).

An additional analysis within each theoretical spacing group revealed that yield per plant marginally increases as the central spacing occupied by a plant expands. However, these increments, while indicative of a potential trend, did not achieve any statistical significance.

Eight out of nine spacing uniformity metrics are significantly correlated with yield per plant ($\alpha = 0.05$, Figure 3.5). Yield per plant was negatively correlated with PSV, plant spacing CV, singles skips, miss, multiples, and precision index, while it was positively correlated with quality of feed (Table 3.2, Figure 3.5). Increasing PSV negatively impacted the yield outcome of each plant ($r = -0.30, p < 0.001$). Consequently, for each unit increase in PSV, the yield per plant decreases by 9.13 g. Likewise, spacing CV also shows a negative impact on yield ($r = -0.21, p < 0.01$), however, the reduction in yield per unit increase in spacing CV is relatively more severe—78.33 g. These results highlight the relative nature of variability in plant spacing and suggest that managing uneven distribution with respect to actual average spacing is equally crucial as aligning it with theoretical spacing targets. Other non-ideal spacing outcomes such as single skips ($r = -0.16, p < 0.05$), misses ($r = -0.17, p < 0.05$), and multiples ($r = -0.26, p < 0.001$) adversely affected the yield outcomes of each plant. Among these, multiples had the most notable impact—yield per

plant decreased by 4.65 g for every percentage increase in multiples. Higher values of the precision index, another important spacing uniformity indicator, were also associated ($r = -0.16$, $p < 0.05$) with lower yield per plant. In this sense, for every 0.1 unit increase in the precision index, the yield per plant suffered by 18.8 g.

Table 3. 2 Correlation and regression analysis between various indicators of spacing uniformity and yield per plant.

Uniformity metric	Yield Per Plant (g)			
	Correlation		Regression	
	Coefficient (r)	<i>p-value</i>	coefficient (β)	<i>p-value</i>
Plant spacing variation (PSV)	-0.30	< 0.001	-9.13	< 0.001
Spacing CV	-0.21	0.004	-78.33	0.003
Single skips (%)	-0.16	0.027	-1.05	0.027
Miss (%)	-0.17	0.016	-1.08	0.016
Multiples (%)	-0.26	< 0.001	-4.65	< 0.001
Quality (%)	0.24	< 0.001	1.33	< 0.001
Precision index	-0.16	0.026	-188.00	0.026
G-spacing	-0.83	< 0.001	-912.34	< 0.001

Note: The correlation coefficient indicates the direction and strength of the relationship, the regression coefficient quantifies the change in outcome with one unit change in the predictor, and p-values indicate their significance.

G-spacing effectively captures the considerable influence of inequality in plant spacing distribution on yield, as demonstrated by a strong negative correlation ($r = -0.83$, $p < 0.001$) between it and yield per plant. Quantitative analysis indicates that for every 0.1 unit increase in G-spacing, yield per plant decreases by 9.1 g, as shown in Figure 3.5(i). G-spacing together with Lorenz curves thoroughly characterizes the patterns in plant-to-plant spacing inequality. The corresponding variabilities in plant-to-plant yield are also illustrated by G-yield, SD of yield per plant, and its CV. Higher inequalities in plant spacing, as indicated by greater G-spacing values, correspond to larger variabilities in yield per plant. For Exp 2, the comparison of Lorenz curves indicates greater inequality in yield distribution per plant at operational settings of high speed combined with low downforce compared to low speed combined with moderate downforce—

Figure 3.3(d). Figures 3.3(e) and 3.3(f) present the frequency distributions of yield for the two operational settings, respectively. The average yield per plant at low speed and moderate downforce is 183.43 ± 51.34 g, with 50 % of the yield units concentrated in a range between 149.27 to 217.88 g. Similarly, at high speed and low downforce settings, the average yield per plant is 170.47 ± 77.11 g with half of the yield units accumulated within a range of 119.65 to 232.75 g. For the low-yielding combination, the Lorenz curve—Figure 3.3(d), shows that the bottom 30 % of plants contribute only 13 % to the total yield, while the bottom 50 % of plants collectively account for slightly more, yet a disproportionate 31 %. Conversely, for high-yielding combinations, these contributions increase to 20 % and 40 % respectively.

Lorenz curves in Figure 3.4(j) and corresponding histograms for yield distributions—Figures 3.4(k) and 3.4(l) underscore the yield disparities at high and low-yielding operation settings. Under the low speed and moderate downforce settings, the average yield per plant is 116 ± 33.26 g with the interquartile range between 97.28 to 135.32 g. Likewise, at high speed and low downforce settings, the average yield per plant is 115.97 ± 39.66 g with half of the values concentrated within a range of 96.81 to 143.9 g. Figure 3.4(j) shows that for both operational settings, the top 20 % show similar yield contributions—28 % to the total yield. However, the inequality in yield distribution between the operational settings is apparent in the bottom 80 % of the plant population.

For both experiments, Lorenz curves and the Gini index demonstrate that the variability in plant spacing translates to variability in yield outcomes. The significant correlation between SD ($r = -0.81$, $p < 0.001$) and CV ($r = -0.77$, $p < 0.001$) of plant-to-plant spacing with yield per plant further affirms this finding. Moreover, higher inequality in yield outcomes was also associated with a broader range of yield per plant and the distributions exhibit bimodality. In the same way,

higher Gini indexes for spacing and yield consistently correspond to greater values of CV and SD values.

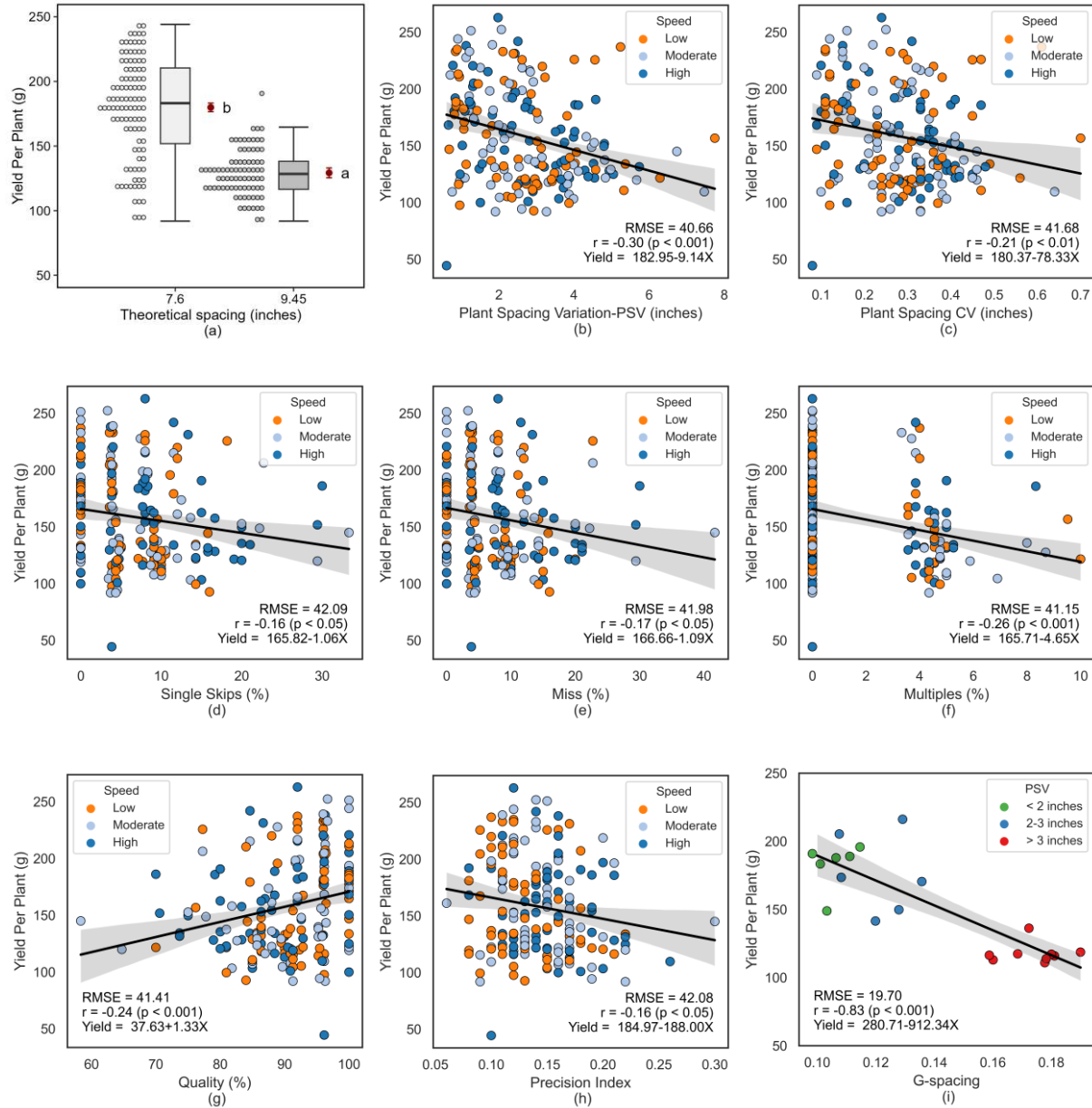


Figure 3. 5 Relationship of corn yield per plant with plant spacing and different indicators of spacing uniformity combined across Exp. 1 and Exp. 2. (a) Theoretical plant spacing, (b) plant spacing variation, (c) plant spacing CV, (d) single skips percentage, (e) miss percentage, (f) multiples percentage, (g) quality percentage, (h) precision index, and (i) Gini index of spacing.

Discussion

The findings from this study suggest that the choice of operational settings for a planter significantly influences the uniformity in corn plant spacing. Most of the stand consistency indicators declined linearly with an increase in planting speed. At all levels of planting speeds, the spacing CV remained consistent, suggesting a corresponding increase in average plant-to-plant spacing along with PSV as the planter approached faster speeds. Faster speeds can induce excessive vibration in the row units and within the seed meters leading to inconsistent pickup and releases. It causes the seed to ricochet along the seed tube, inaccurately dropping it in the furrow at irregular intervals thereby compromising spacing uniformity. Staggenborg et al. (2004) reported a decline in seed metering efficiency as planter speed increased resulting in greater plant spacing SD. However, a slight improvement in spacing SD (0.3 in.) was observed when the planter was equipped with seed firmer. These findings are consistent with Badua et al. (2021) who noted higher variability and wider spacing at elevated planting speeds. Although not statistically significant, both PSV and CV of spacing showed slight improvements at higher downforce settings. The improvements could be attributed to better stabilization and improved ride quality at those downforce levels.

The precision index was affected by both planter speed and downforce settings, with higher levels of each associated with poorer precision indexes. Nevertheless, these values did not exceed the practical limit (S. D. Kachman & J. A. Smith, 1995) of 29 % indicating a good target seed delivery by the planter. Kovács & Casteel (2023) who evaluated high-speed planter in soybean planting, also observed an increase in the precision index (22.5—25 %) when planting speed increased from 5 mph to 10 mph. Another indicator of planter performance—miss percentage, was 7.4 % at lower speeds but increased to 9.34 % as speed levels reached high. However, with

increasing downforce levels, the miss percentage fell by 2 %. Staggenborg et al (2004) also observed an increase in the number of misses by 1.9 and multiples by 1.2 for each mile increase in planting speed. Faster planting speeds increase the rotational speed of seed metering units, which influences the singulation process resulting in higher percentages of miss and multiples. However, it is important to note that with post-emergence spacing measurements, an inflation of the miss percentage can occur due to factors like emergence failure, post-emergence but pre-measurement mortality, or the planter failing to properly deliver the seed to the trench (Kovács & Casteel, 2023; Staggenborg et al., 2004; Virk et al., 2020). The marginal reduction in miss and multiple percentages at higher downforce levels is potentially due to improved seed-to-soil contact, and fewer dislodged seeds resulting from minimal disturbance to furrow shape (Badua et al., 2021; Poncet et al., 2019; Virk et al., 2021).

The broader findings of the study support the hypothesis that within-row variability of corn plant spacing is associated with lower yield outcomes for each plant. Plants that are spaced too close experience intense intra-specific competition for growth resources like nutrients, water, and sunlight. This can result in stunted shoots, smaller ears with fewer kernels, a higher mortality rate, and a lower harvest index. It also introduces size asymmetry between plant populations eventually leading to increased variation in individual yield (Lu et al., 2020; Tokatlidis, 2022). Conversely, as corn is anemophilous, the wider spacing could impact pollination efficiency, potentially reducing kernel set. Moreover, wider spacing delays canopy closure, creating an opportunity for weed proliferation, which further causes resource deficiency at the grain-filling stage (Ren et al., 2022).

The observations on the impact of spacing variation on the yield of each plant align with findings published in earlier studies. Liu et al. (2004a) reported a reduction in yield by 40.64

kg/acre (39.5 kg/hectare per cm) for every inch increase in spacing SD. Comparably, Nielsen (2004) observed a reduction of 64.24 kg/acre (62 kg/hectare per cm). Novak & Ransom (2018) concluded that within-row spacing variability impacts individual ear weight causing an overall yield loss. Further, for a 36 % variability in plant density, a yield decline of 4 % was noted.

Lorenz curves and the Gini index prove to be effective indices for analyzing the magnitude and distribution of inequalities in plant spacing and yield disparities among plants. These indices successfully detected the differences in spatial distribution and its impact on plant yield, thereby identifying optimal operational settings. Higher planting speeds induce row unit vibrations, and coupled with low downforce, it can increase spacing inconsistency due to poor ground contact. In contrast, operational settings of low speed and moderate downforce stabilize the planter ensuring a better seed-to-soil engagement and improving spatial uniformity. Inferences obtained using the Gini index and all other traditional uniformity metrics converge.

Lorenz curves complement the Gini index by providing an agronomic interpretation of the relative contribution of individual plants to overall yield. Together with spatial analytical tools like GIS yield maps, Lorenz curves can be used to identify sections of the field with significantly low-yielding plants. These disparities can be addressed with tailored site-specific farm management practices resulting in better resource allocation and optimal crop performance.

Conclusion

The assessment of plant-to-plant spacing inequality using Lorenz curves and the Gini index reveals significant variability across different combinations of planting speed and applied downforce. Lower planting speeds coupled with moderate downforce settings minimized spacing inequality as evidenced by lower G-spacing values, and relatively minimal deviations of Lorenz

curves from the line of equality. The consistent deterioration of the precision index along with the increase in miss and multiple percentages at faster planting speeds also supports this inference.

Corn yield at the plant level was significantly and negatively correlated with within-row plant spacing variability. Non-ideal spacing outcomes like missing plants and multiples also negatively impacted corn yield. Consequently, an inverse relationship between G-spacing and yield per plant was observed with regression analysis. Increased spatial variability contributed to a rise in inequality of yield outcome among individual plants. A broader range of yield per plant associated with higher spacing inequality also highlighted this disparity. The inequality can be attributed to individual plant size variation stemming from intense competition for growth resources.

In summary, the study indicates an indirect influence of planter operation settings—planting speed and applied downforce—on corn yield through its impact on plant-to-plant spacing inequality. The extent of yield loss is accentuated as the inequality in spacing rises. The Lorenz curve and Gini index framework was effective in identifying these findings and can complement uniformity metrics based on distribution moments.

Chapter 4 - Conclusion

Summary of Findings

The purpose of this study was twofold: first to identify the optimal operational parameters for a row crop planter that consistently achieves target seeding depth. Second, to assess the impact of such parameters on within-row spacing variability and evaluate yield disparities.

The choice of planting speed and downforce settings significantly influence how precisely and consistently seeds are placed in the furrow. Lower planting speeds produce uniform seeding depth. Both magnitude and consistency of seeding depth suffer as the planter transitions to higher speeds. The deterioration in seeding depth can be compensated by increasing downforce. Higher levels of downforce consistently lead to deeper depths, however, the variability of depth too increased at higher levels of downforce. The optimal values for operation parameters—downforce and planting speed, vary distinctly across the three sections of the planter—non-track, track, and wing sections. Specifically, the track section benefits from lower planting speeds for bias minimization. The differences are slightly more pronounced for 16-RP when compared with 24-RP.

The assessment of plant-to-plant spacing inequality reveals significant variability across different combinations of planting speed and applied downforce. Lower planting speeds coupled with moderate downforce settings minimize spacing inequality.

Corn yield at the plant level significantly and negatively correlates with within-row plant spacing variability. Non-ideal spacing outcomes like missing plants and multiples also negatively impact corn yield. Increased spatial variability contributes to a rise in inequality of yield outcomes among individual plants. Planter operation settings—planting speed and applied downforce,

indirectly influence corn yield through its impact on plant-to-plant spacing inequality. The extent of this yield loss increases as the inequality in spacing rises.

References

- Abendroth, L. J., Elmore, R. W., Boyer, M. J., & Marlay, S. K. (2011). Corn Growth and Development: Crop Staging | Agronomic Crops Network. In *Corn Growth and Development*. Iowa State University Extension. <https://agcrops.osu.edu/newsletter/corn-newsletter/2022-18/corn-growth-and-development-crop-staging>
- Alain F. Zuur, Zuur, A. F., Elena N. Ieno, Ieno, E. N., N. P. J. Walker, Walker, N. J., Anatoly A. Saveliev, Saveliev, A. A., Graham M. Smith, & Smith, G. M. (2009). *Mixed Effects Models and Extensions in Ecology with R*.
- Ali, S. A. M., & Idris, A. Y. (2015). *Effect of Seed Size and Sowing Depth on Germination and Some Growth Parameters of Faba Bean (Vicia faba L.)*. 1(1).
- Andrade, F. H., Pablo Eduardo Abbate, & Abbate, P. E. (2005). Response of maize and soybean to variability in stand uniformity. *Agronomy Journal*, 97(4), 1263–1269. <https://doi.org/10.2134/agronj2005.0006>
- Badua, S. 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>
- 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>
- Banerjee, B. P., Sharma, V., Spangenberg, G., & Kant, S. (2021). Machine Learning Regression Analysis for Estimation of Crop Emergence Using Multispectral UAV Imagery. *Remote Sensing*, 13(15), 2918. <https://doi.org/10.3390/rs13152918>
- Ben Rosser. (2021, April 13). *Agronomy Guide For Field Crops – Corn – Emergence and Spacing Uniformity, Replant Decisions – Field Crop News*. <https://fieldcropnews.com/2021/04/agronomy-guide-for-field-crops-corn-emergence-spacing-replant-decisions/>
- Bernard Pommel, Pommel, B., & Bouchard, C. (1990). Influence du poids de la semence et de la profondeur de semis sur la croissance et le développement de la plantule de maïs. *Agronomie*, 10(9), 699–706. <https://doi.org/10.1051/agro:19900901>

- 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>
- Bond, W. J., Honig, M., & Maze, K. E. (1999). Seed size and seedling emergence: An allometric relationship and some ecological implications. *Oecologia*, 120(1), 132–136. <https://doi.org/10.1007/s004420050841>
- Booth, G. D., Steel, R. G. D., & Torrie, J. H. (1981). Principles and Procedures of Statistics: A Biometrical Approach. *Journal of the American Statistical Association*, 76(375), 753. <https://doi.org/10.2307/2287561>
- Borgan, Ø., Breslow, N., Chatterjee, N., Gail, M. H., Scott, A., & Wild, C. J. (Eds.). (2020). *Handbook of Statistical Methods for Case-Control Studies* (1st edition). Routledge.
- Box, G. E. P., & Wilson, K. B. (1951). On the Experimental Attainment of Optimum Conditions. *Journal of the Royal Statistical Society: Series B (Methodological)*, 13(1), 1–38. <https://doi.org/10.1111/j.2517-6161.1951.tb00067.x>
- Brandelero, E. M., Adami, P. F., Modolo, A. J., Murilo Mesquita Baesso, Murilo Mesquita Baesso, Baesso, M. M., Adelar José Fabian, Fabian, A. J., & Adelar José Fabian. (2015). Seeder Performance under Different Speeds and its Relation to Soybean Cultivars Yield. *Journal of Agronomy*, 14(3), 139–145. <https://doi.org/10.3923/ja.2015.139.145>
- Brilhador, A., Serrarens, D. A., & Lopes, F. M. (2015). A Computer Vision Approach for Automatic Measurement of the Inter-plant Spacing. In A. Pardo & J. Kittler (Eds.), *Progress in Pattern Recognition, Image Analysis, Computer Vision, and Applications* (pp. 219–227). Springer International Publishing. https://doi.org/10.1007/978-3-319-25751-8_27
- Bruno Walther, Walther, B. A., Joslin L. Moore, & Moore, J. L. (2005). The concepts of bias, precision and accuracy, and their use in testing the performance of species richness estimators, with a literature review of estimator performance. *Ecography*, 28(6), 815–829. <https://doi.org/10.1111/j.2005.0906-7590.04112.x>
- Carreira, V. D. S., Tedesco, D., Carreira, A. D. S., & da Silva, R. P. (2022). Assessing Intra-Row Spacing Using Image Processing: A Promising Digital Tool for Smallholder Farmers. *Agronomy*, 12(2), Article 2. <https://doi.org/10.3390/agronomy12020301>

- Carter, P. R., D. Nafziger, E., & Lauer, J. G. (1990). *Uneven Emergence in Corn* (Extension 344; North Central Regional Extension Publication). <http://corn.agronomy.wisc.edu/Pubs/UWEX/NCR344.pdf>
- Chan, F. J., Harris, R. W., Leiser, A. T., & Paul, J. L. (1969). Factors Influencing Depth of Seeding. *Tree Planters' Notes*, 20(2). <https://rngr.net/publications/tpn/20-2>
- Coronel, E. G., Alesso, C. A., Bollero, G. A., Armstrong, K. L., & Martin, N. F. (2020). Field-specific yield response to variable seeding depth of corn in the Midwest. *Agrosystems, Geosciences & Environment*, 3(1), e20034. <https://doi.org/10.1002/agg2.20034>
- 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>
- Damgaard, C., & Weiner, J. (2000). Describing Inequality in Plant Size or Fecundity. *Ecology*, 81(4), 1139–1142. [https://doi.org/10.1890/0012-9658\(2000\)081\[1139:DIIPSO\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2000)081[1139:DIIPSO]2.0.CO;2)
- Dean, A., Voss, D., & Draguljić, D. (2017). *Design and Analysis of Experiments*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-52250-0>
- Diggle, P. J., & Ribeiro, P. J. (2007). *Model-based geostatistics*. Springer.
- Doerge, T., Jeschke, M., & Carter, P. (2015). *Planting Outcome Effects on Corn Yield*. <https://www.semanticscholar.org/paper/Planting-Outcome-Effects-on-Corn-Yield-Doerge-Jeschke/ba7f3da0116b4899cd7f6273ab578b120a5a9be1>
- Drost, D., & Alston, D. (2021). *2020-21 UTAH VEGETABLE PRODUCTION AND PEST MANAGEMENT GUIDE*.
- Dufour, J. (2021). *Effects of Plant Spacing Variability and Non-Uniform Emergence on Corn Yield* [Master of Science, Louisiana State University and Agricultural and Mechanical College]. https://doi.org/10.31390/gradschool_theses.5410
- Emrah Kuş. (2021). Optimization of Operational Parameters of a Vacuum Single-Seed Planter for Sowing of Maize. *Journal of Agricultural Sciences*, 27(3), 327–334. <https://doi.org/10.15832/ankutbd.678544>
- Fancelli, A. L. (2000). Crop Physiology and Basic Aspects of Management for High. In *Maize Crop: Management Strategies for the South Region* (pp. 103–106). Fundação Agrária de Pesquisa Agro-Pecuária.

- Forcella, F., Benech Arnold, R. L., Sanchez, R., & Ghera, 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)
- Grassbaugh, E. M., & Bennett, M. A. (1998). Factors affecting vegetable stand establishment. *Scientia Agricola*, 55, 116–120. <https://doi.org/10.1590/s0103-90161998000500021>
- Hanna, H. M., Steward, B. L., Brian S Steward, & Aldinger, L. (2008). *Soil Loading Effects of Planter Depth-Gauge Wheels on Early Corn Growth*. 1. <https://doi.org/10.13031/2013.24631>
- Haye, R. L., & Zizler, P. (2021). Applications of the Gini Index Beyond Economics and Statistics. In B. Sriraman (Ed.), *Handbook of the Mathematics of the Arts and Sciences* (pp. 1661–1689). Springer International Publishing. https://doi.org/10.1007/978-3-319-57072-3_103
- Hoshmand, R. (1997). *Statistical Methods for Environmental and Agricultural Sciences* (2nd ed.). CRC Press. <https://doi.org/10.1201/9780203738573>
- ISO 7256. (1984). *ISO 7256-1:1984*. ISO. <https://www.iso.org/standard/13910.html>
- Itabari, J. K., Gregory, P. J., & Jones, R. K. (1993). Effects of Temperature, Soil Water Status and Depth of Planting on Germination and Emergence of Maize (*Zea Mays*) Adapted to Semi-Arid Eastern Kenya. *Experimental Agriculture*, 29(3), 351–364. <https://doi.org/10.1017/S0014479700020913>
- Jambrak, A. R. (2011). Experimental Design and Optimization of Ultrasound Treatment of Food Products. *Journal of Food Processing & Technology*, 02(03). <https://doi.org/10.4172/2157-7110.1000102e>
- James P Shroyer, Thompson, C., & Brown, R. (1996). *Kansas Crop Planting Guide*. <https://bookstore.ksre.ksu.edu/pubs/l818.pdf>
- Jeschke, M. (2021). *Corn Planting Depth*. Corn Planting Depth. <https://www.pioneer.com/us/agronomy/corn-planting-depth.html>
- Karayel, D., & Šarauskis, E. (2011). *Effect of downforce on the performance of no-till disc furrow openers for clay-loam and loamy soils*. 43(3), 16–24.
- 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>
- Kovács, P., & Casteel, S. N. (2023). Evaluation of a high-speed planter in soybean production. *Agronomy Journal*, 115(3), 1174–1187. <https://doi.org/10.1002/agj2.21313>
- Lamb, K. E., & Johnson, B. L. (2004). Seed Size and Seeding Depth Influence on Canola Emergence and Performance in the Northern Great Plains. *Agronomy Journal*, 96(2), 454–461. <https://doi.org/10.2134/agronj2004.4540>
- Lauer, J. (2002). *With-in Row Plant Spacing in Corn*.
- Lauer, J. G., & Rankin, M. (2004). Corn Response to Within Row Plant Spacing Variation. *Agronomy Journal*, 96(5), 1464–1468. <https://doi.org/10.2134/agronj2004.1464>
- Liu, M., Su, W.-H., & Wang, X.-Q. (2023). Quantitative Evaluation of Maize Emergence Using UAV Imagery and Deep Learning. *Remote Sensing*, 15(8), 1979. <https://doi.org/10.3390/rs15081979>
- Liu, W., Tollenaar, M., Stewart, G., & Deen, W. (2004a). Impact of Planter Type, Planting Speed, and Tillage on Stand Uniformity and Yield of Corn. *Agronomy Journal*, 96(6), 1668–1672. <https://doi.org/10.2134/agronj2004.1668>
- Liu, W., Tollenaar, M., Stewart, G., & Deen, W. (2004b). Within-Row Plant Spacing Variability Does Not Affect Corn Yield. *Agronomy Journal*, 96(1), 275–280. <https://doi.org/10.2134/agronj2004.2750>
- Lorenz, M. O. (1905). Methods of Measuring the Concentration of Wealth. *Publications of the American Statistical Association*, 9(70), 209–219. <https://doi.org/10.2307/2276207>
- Lu, P., Jiang, B., & Weiner, J. (2020). Crop spatial uniformity, yield and weed suppression. In *Advances in Agronomy* (Vol. 161, pp. 117–178). Elsevier. <https://doi.org/10.1016/bs.agron.2019.12.003>
- M. F. Kocher, J. M. Coleman, J. A. Smith, & S. D. Kachman. (2011). Corn Seed Spacing Uniformity as Affected by Seed Tube Condition. *Applied Engineering in Agriculture*, 27(2), 177–183. <https://doi.org/10.13031/2013.36484>
- Mapoka, K. O. M. (2018). *Nondestructive measurement system to determine corn seed planting depth using ground penetrating radar for precision agriculture*.

- Masilamani, P., Venkatesan, S., Navamaniraj, K. N., Rajarathinam, P., Alagesan, A., & Thiagu, K. (2023). Impact of the orientation of seed placement and depth of its sowing on germination: A review. *Journal of Applied and Natural Science*, 15(1), 314–324. <https://doi.org/10.31018/jans.v15i1.4265>
- Masino, A., Pablo Rugeroni, Rugeroni, P., Lucas Borrás, Borrás, L., José L. Rotundo, & Rotundo, J. L. (2018). Spatial and temporal plant-to-plant variability effects on soybean yield. *European Journal of Agronomy*, 98, 14–24. <https://doi.org/10.1016/j.eja.2018.02.006>
- Mishler, B. (2021). *BradenMishler2021.pdf*. Kansas State University.
- Molatudi, R. L., & Mariga, I. K. (2009). The effect of maize seed size and depth of planting on seedling emergence and seedling vigour. *The Journal of Applied Sciences Research*, 2234–2237.
- Monsanto. (2009). *2009 Demonstration Report—Corn Planting Depth and Final Population Yield*.
- Montgomery, D. C. (2013). *Design and analysis of experiments* (Eighth edition). John Wiley & Sons, Inc.
- Morrison, J. E., & Gerik, T. J. (1985). Planter Depth-Control: I. Predictions and Projected Effects on Crop Emergence. *Transactions of the ASABE*, 28(5), 1415–1418. <https://doi.org/10.13031/2013.32452>
- Mutema, A. (2015). *Effects of seed kernel size and planting depth on the germination, emergence and early growth performance of maize (Zea mays)*.
- Myers, R. H. (2016). *Response Surface Methodology*.
- Nafziger. (2009). *Illinois agronomy handbook: 24th edition* (24th ed.). University of Illinois at Urbana-Champaign, College of Agriculture, Cooperative Extension Service.
- 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, B. (1995). Planting Speed Effects on Stand Establishment and Grain Yield of Corn. *Journal of Production Agriculture*, 8(3), 391–393. <https://doi.org/10.2134/jpa1995.0391>
- Nielsen, B. (2010). *Requirements for Uniform Germination and Emergence of Corn* (Purdue University). <https://www.agry.purdue.edu/ext/corn/news/timeless/germemergreq.html>

- Nielsen, B. (2020). *The Emergence Process in Corn*.
<https://www.agry.purdue.edu/ext/corn/news/timeless/emergence.html>
- Nielsen, B. (2021). How Deep Should Corn Be Planted? *Pest&Crop Newsletter*.
<https://extension.entm.purdue.edu/newsletters/pestandcrop/article/how-deep-should-corn-be-planted/>
- Nielsen, R. L. (2004). *Effect of Plant Spacing Variability on Corn Grain Yield*. d
- 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>
- Özmerzi, A., Karayel, D., & Topakci, M. (2002). Effect of sowing depth on precision seeder uniformity. *Biosystems Engineering*.
- Pereyra, V. M., Bastos, L. M., Bastos, L. M., Reis, A. F. de B., Ricardo J. M. Melchiori, Roberto Melchiori, Nicolas E. Maltese, Nicolás Maltese, Stefania C. Appelhans, Stefania Carolina Appelhans, P. V. Vara Prasad, P. V. Vara Prasad, Yancy Wright, Yancy Wright, Edwin Brokesh, Edwin Brokesh, Ajay Sharda, Ajay Sharda, Ignacio A. Ciampitti, & Ignacio A. Ciampitti. (2022). Early-season plant-to-plant spatial uniformity can affect soybean yields. *Scientific Reports*, 12(1). <https://doi.org/10.1038/s41598-022-21385-z>
- Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., EISPACK, sigma), S. H. (Author fixed, sigma), B. V. W. (Programmer fixed, Ranke (varConstProp()), J., & R Core Team. (2023). *nlme: Linear and Nonlinear Mixed Effects Models* (3.1-164) [Computer software]. <https://cran.r-project.org/web/packages/nlme/index.html>
- 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>
- Quanwei, L., Xiaoyun He, Xiantao, H., Yang Li, Li, Y., Dongxing, Z., Tao, C., Zhe, Q., Bingxin, Y., Mantao Wang, Mantao, W., & Tianliang, Z. (2017). Effect of travel speed on seed

- spacing uniformity of corn seed meter. *International Journal of Agricultural and Biological Engineering*, 10(4), 98–106. <https://doi.org/10.25165/ijabe.v10i4.2675>
- R Core Team. (2023). *A Language and Environment for Statistical Computing* [R]. R Foundation for Statistical Computing. <https://www.r-project.org/>
- Ren, H., Zhao, M., Zhou, B., Zhou, W., Li, K., Qi, H., Jiang, Y., & Li, C. (2022). Understanding physiological mechanisms of variation in grain filling of maize under high planting density and varying nitrogen applicate rate. *Frontiers in Nutrition*, 9. <https://doi.org/10.3389/fnut.2022.998946>
- S. D. Kachman & J. A. Smith. (1995). Alternative Measures of Accuracy in Plant Spacing for Planters Using Single Seed Metering. *Transactions of the ASAE*, 38(2), 379–387. <https://doi.org/10.13031/2013.27843>
- Sadras, V., & Bongiovanni, R. (2004). Use of Lorenz curves and Gini coefficients to assess yield inequality within paddocks. *Field Crops Research*, 90(2–3), 303–310. <https://doi.org/10.1016/j.fcr.2004.04.003>
- Sáenz Rodríguez, M. N., & Cassab, G. I. (2021). Primary Root and Mesocotyl Elongation in Maize Seedlings: Two Organs with Antagonistic Growth below the Soil Surface. *Plants*, 10(7), 1274. <https://doi.org/10.3390/plants10071274>
- Sandell, L., Jasa, P., & Jarvi, K. (2015, September 17). *Shallow Planting Can Contribute to Larger Problems*. CropWatch. <https://cropwatch.unl.edu/shallow-planting-can-contribute-larger-problems>
- Sangoi, L., Gracietti, M. A., Rampazzo, C., & Bianchetti, P. (2002). Response of Brazilian maize hybrids from different eras to changes in plant density. *Field Crops Research*, 79(1), 39–51. [https://doi.org/10.1016/S0378-4290\(02\)00124-7](https://doi.org/10.1016/S0378-4290(02)00124-7)
- 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>
- Sen, A., & Foster, J. E. (1973). *On Economic Inequality*.
- Sharma, S., Warren, J., Lofton, J., Henry, W., & Murley, C. (2019). *Optimum planting depth for uniform germination and emergence of corn*. <https://shareok.org/handle/11244/332241>
- Silva, R. P. da, Corá, J. E., Carvalho Filho, A., Lopes, A., & Furlani, C. E. A. (2004). Efeito de rodas compactadoras submetidas a cargas verticais em profundidades de semeadura sobre

- o desenvolvimento do milho. *Engenharia Agrícola*, 24, 396–404. <https://doi.org/10.1590/S0100-69162004000200019>
- Silveira, J. C. M. da, Haroldo Carlos Fernândes, Fernandes, H. C., Fernandes, H. C., Alcir José Modolo, Modolo, A. J., Modolo, A. J., Alcir José Modolo, Alcir José Modolo, Suedêmio de Lima Silva, de Lima Silva, S., Trogello, E., & Trogello, E. (2011). *Profundidade de sulco, área de solo mobilizada e força de tração de uma semeadora-adubadora em razão da velocidade de deslocamento*. 58(3), 293–298. <https://doi.org/10.1590/s0034-737x2011000300008>
- Sitthiyot, T., & Holasut, K. (2021). A simple method for estimating the Lorenz curve. *Humanities and Social Sciences Communications*, 8(1), 268. <https://doi.org/10.1057/s41599-021-00948-x>
- Soignier, T. S., Plumblee, M. T., Mueller, J. D., Greene, J. K., & Kirk, K. R. (2022). The evaluation of planter downforce on emergence and grain yield in soybean. *Crop, Forage & Turfgrass Management*, 8(2), e20186. <https://doi.org/10.1002/cft2.20186>
- Srivastava, A. K., Goering, C. E., Rohrbach, R. P., & Buckmaster, D. R. (2006). *Table of Contents and Preface for Engineering Principles of Agricultural Machines 2nd Edition*. 0. <https://doi.org/10.13031/2013.41478>
- Staggenborg, S. A., Taylor, R. K., Taylor, R. K., Maddux, L. D., & Larry D. Maddux. (2004). Effect of Planter Speed and Seed Firmers on Corn Stand Establishment. *Applied Engineering in Agriculture*, 20(5), 573–580. <https://doi.org/10.13031/2013.17457>
- 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>
- Thomison, P. R. (2012). *Planting Depth Effects on Corn Stand and Grain Yield*. <https://www.pioneer.com/us/agronomy/planting-depth-effects-corn-stand.html>
- Thompson, T. (2014). *Within-row spacing effect on individual corn plant yield* [University of Illinois at Urbana-Champaign]. <https://hdl.handle.net/2142/46614>
- Tokatlidis, I. (2022). Crop resilience via inter-plant spacing brings to the fore the productive ideotype. *Frontiers in Plant Science*, 13. <https://doi.org/10.3389/fpls.2022.934359>

- Torres, G. M. (2012). *Precision planting of maize (Zea mays L.)* [Ph.D., Oklahoma State University].
<https://www.proquest.com/docview/1318463957/abstract/529FD1083932473FPQ/1>
- Urban, M. C. (2015). Accelerating extinction risk from climate change. *Science*, 348(6234), 571–573. <https://doi.org/10.1126/science.aaa4984>
- Van Duc Long, N., Yared Assefa, Assefa, Y., Schwalbert, R., & Ciampitti, I. A. (2017). Maize yield and planting date relationship: A synthesis-analysis for US high-yielding contest-winner and field research data. *Frontiers in Plant Science*, 8, 2106–2106. <https://doi.org/10.3389/fpls.2017.02106>
- 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. S., Porter, W. M., Li, C., Rains, G. C., Snider, J. L., & Whitaker, J. R. (2021). On-farm evaluation of planter downforce in varying soil textures within grower fields. *Precision Agriculture*, 22(3), 777–799. <https://doi.org/10.1007/s11119-020-09755-x>
- Wanjura, D. F. (1982). Reduced Cotton Productivity from Delayed Emergence. *Transactions of the ASABE*, 25(6), 1536–1539. <https://doi.org/10.13031/2013.33762>
- Weiner, J., Otto T. Solbrig, & Solbrig, O. T. (1984). The meaning and measurement of size hierarchies in plant populations. *Oecologia*, 61(3), 334–336. <https://doi.org/10.1007/bf00379630>
- Wood, A. (2023, March 13). *Plant Population and Seed Spacing Impact on Corn Yield*. Plant Population and Seed Spacing Impact on Corn Yield. <https://pasquotank.ces.ncsu.edu/2023/03/plant-population-and-seed-spacing-impact-on-corn-yield/>
- Zhang, Q., Zhang, Q., Lizhen Zhang, Zhang, L., Jochem B. Evers, Evers, J. B., Wopke Van der Werf, van der Werf, W., Weiqiang Zhang, Zhang, W., Duan Liu, & Duan, L. (2014). Maize yield and quality in response to plant density and application of a novel plant growth regulator. *Field Crops Research*, 164(164), 82–89. <https://doi.org/10.1016/j.fcr.2014.06.006>