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Planting depth and within-field soil variability impacts on corn stand establishment and yield

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Abstract

Seedbed conditions during corn (*Zea mays* L.) planting can have substantial impact on corn stand establishment and final yield. Planting management decisions are complex due to spatial variability caused by changing soil characteristics such as soil texture or landscape position. Field experiments conducted in central Missouri from 2017 to 2019 assessed the effects of varying corn planting depths on stand establishment and yield. Sites included fine- and coarse-textured alluvial soils, and summit, back, and foot slope positions of Alfisol claypan soil landscapes. On alluvial soil, deep planting (7.6 cm) often had the most uniform and timely emergence. Shallow planting (3.8 cm) had the least uniform emergence and was particularly troublesome on fine-textured soil under warm conditions. Under these conditions, grain yield for one site-year was 2.8 Mg ha^{-1} less when planting shallow compared with planting deep. On the claypan landscape position study, stand establishment was affected by both warm and cool growing conditions during the emergence period. During warm conditions, deep planting enhanced emergence uniformity and rate (1.1 d less to reach 90% emergence than shallow planting); the opposite was true for cool conditions (3.7 d more). Yield was not affected by planting depth at any of the site-years of the landscape position study. These results indicate that certain soil textures and landscape positions require greater attention to planting depth to achieve optimum stand establishment. Differences could be used in on-the-go planter prescriptions. These findings also demonstrate that despite early establishment differences, stands can often compensate and maintain similar yield.

1 | INTRODUCTION

Initial phases of corn (*Zea mays* L.) germination and emergence are crucial for maintaining optimum corn yield (Thomason et al., 2008). The first of these phases, germination, is initiated by involuntary water imbibition. The rate of this water uptake is dependent on soil temperature and is contingent upon seed-to-soil contact (Hayhoe et al., 1993). Hospitable conditions for germination occur when seed-zone soil temperatures are 20–30 ˚C and soil moisture is near field capacity (Schneider & Gupta, 1985). Additionally, plant available water is more important for germination than the volume of soil water present (Knappenberger & Köller, 2008). Minimum values for mean soil temperature and matric potential enabling corn germination are 10 ˚C and −1.5 MPa, respectively (Knappenberger & Köller, 2008).

As corn seeds imbibe water, they become less tolerant to cold stress because chilled water reduces seedling vigor. Typically, soil temperatures >10 ˚C accompanied with a favorable 24- to 48-h weather forecast after planting will avoid chilling injury (Stoll & Saab, 2014). Cool temperatures, as well as excessively wet or dry moisture conditions, lead to slow germination, physiological deformities, and seedling death (Hoeft et al., 2000).

In addition to the direct effects of moisture and temperature, other soil factors influence the corn seedling germination and emergence process including texture, aggregate size, and bulk density (Hadas, 2004). Composition of soil particle size in the form of sand, silt, and clay percentage (i.e., texture) has a considerable influence on soil temperature and water content (Brady & Weil, 2002). Seedling emergence may be reduced in clay soils when planting is followed by a heavy rain that deteriorates soil structure. This can lead to a compacted or "sealed" soil surface layer, often referred to as "soil crusting" (Parker & Taylor, 1965). Under these conditions, seed may encounter less available water and insufficient force to emerge through the soil surface (Hadas, 2004). Various cultural practices, including tillage method or the inclusion of cover crops, also influence the abovementioned soil properties. For example, Dam et al. (2005) found slower corn emergence rates in no-till compared with tillage because of cool and buffered soil temperatures. Also, crop residues can negatively affect corn emergence by reducing seed-to-soil contact (Swan et al., 1996).

Current University Extension and industry recommendations in many Midwestern states suggest a minimum planting depth of 3.8–5.1 cm to ensure crown and nodal roots develop at a soil depth of 2 cm (Cox & Cherney, 2015; Pioneer, 2013; Thomison et al., 2013). However, most corn hybrids are capable of emergence from depths of 10–13 cm if soil conditions are ideal, although planting depth may affect emergence timeliness and uniformity (Hoeft et al., 2000). Choosing the appropriate planting depth is a challenge accentuated by in-field variability of soil conditions on the day of planting. This variability can encompass both optimal and sub-optimal planting environments.

Like many corn production fields throughout the world, Missouri fields in the U.S. Midwest often contain soil–landscape variability within fields that create soil moisture and temperature differences (Sudduth et al., 2001). Productive alluvial soils near large rivers and streams typically contain large within-field texture variation (e.g., from high sand to high clay content) (Miller & Krusekopf, 1918). Similarly, Missouri claypan soil landscapes have a highly variable topsoil depth (i.e., depth to a pronounced argillic horizon) that relates to grain productivity (Jamison et al., 1968; Kitchen et al., 1999). These soils are susceptible to drought during dry conditions and prolonged saturation during wet conditions. Furthermore, runoff and subsurface lateral flow from upslope positions can result in ponding at low-lying foot slope areas (Nikiforoff & Drosdoff, 1943). When wet conditions occur after planting, corn emergence slows and yield is suppressed (Kitchen et al., 1999).

Core Ideas

- On alluvial soils, planting deep typically resulted in the most uniform emergence.
- On alluvial soils, planting shallow in fine-textured soil was vulnerable to poor emergence.
- On claypan soil landscapes, planting deep if warm and shallow when cold gave the best emergence.
- Fields with high soil variation warrant variable planting depth, guided by weather forecasts.

Planting operations that take into account within-field soil variability may allow for more uniform crop stands (Nemergut et al., 2021). In recent years, planters have switched from conventional downforce springs to hydraulic or pneumatic downforce systems to enable active in-field adjustments (Poncet et al., 2019). With these new downforce technologies, the seedbed environment is managed by maintaining consistent planting depth across variable soil conditions. Additional planter features include technologies enabling seed singulation, row-to-row monitoring, and variable rate populations. Obtaining real-time soil characteristics is also now available through soil-sensing technology (e.g., SmartFirmer, Precision Planting). The SmartFirmer houses multiple sensors to estimate soil properties in the seedbed environment, including soil temperature, moisture status, organic matter, and cleanness of the furrow. Few reports exist documenting the accuracy of this new sensing technology; however, other similar real-time sensors were found helpful for changing planting depth in response to excessive soil moisture (René-Laforest, 2015). More recently, a new product available commercially called SmartDepth (Precision Planting) works in coordination with the SmartFirmer and offers real-time planting depth adjustments.

Although active planting depth adjustment is quickly becoming a reality, agronomic guidelines for how and when to make those adjustments based on within-field soil conditions are largely undeveloped. Thus, research is needed to better quantify relationships between within-field soil variability and planting depth on corn emergence and stand characteristics in order to maximize emerging planter technologies. The primary objective of this study was to determine the influence of corn planting depth and within-field soil variability on corn stand establishment and grain yield.

2 | MATERIALS AND METHODS

Research was conducted in central Missouri during the 2017–2019 growing seasons. Two separate studies were conducted examining within-field variability of soil and planting depth on corn emergence and yield. The first, called the soil texture study, was conducted on fields with variable soil texture due to alluvial parent material adjacent to the Missouri River (i.e., Entisol or Inceptisol). The second, called the landscape position study, was performed on fields with highly weathered loess parent material (i.e., Alfisol) over a landscape toposequence that had been variably eroded because of tillage. The soils across this toposequence include a distinctive (typically greater than two times more clay content than horizon above) and abrupt (i.e., within 2 cm) subsoil argillic horizon, the source of the commonly used name "claypan soils." Table 1 provides descriptive information for each field study site.

2.1 | Soil texture study

Research was conducted in 2017 and 2018 on a farm near Claysville, MO (38.6582˚ lat., –92.2436˚ long.) with two contrasting soil textures (sand/sandy loam and loam) within the same general field (~0.5 km apart). Soil apparent electrical conductivity (soil EC_a) was measured with a Veris 3100 (Veris Technologies) across a large area to identify and establish uniform plot areas within each of the two contrasting soil textures. Soil texture analysis values ranged from 73.0 to 92.9% sand on the coarse-textured site, and 19.7 to 26.9% clay on the fine-textured site (Table 1). The coarse-textured soil was mapped as a Sarpy soil series (mixed, mesic Typic Udipsamments; Soil Survey Staff, 2002), and the fine-textured soil was mapped as a Peers soil series (fine-silty, mixed, superactive, mesic Fluvaquentic Hapludolls; Soil Survey Staff, 2002).

Within each soil texture location, planting depth treatments were targeted at 3.8, 5.1, 6.4, and 7.6 cm, with four replications arranged in a randomized complete block design. Each plot was 9.1 m long and four 0.76-m rows wide. Seeding was performed with a custom-built four-row planter, equipped with MaxEmerge XP row units (Deere & Company). Modifications in 2018 replaced the original equipment manufacturer's heavy-duty downforce springs with a hydraulic downforce system (DeltaForce, Precision Planting) to increase planting depth consistency. Missouri River flooding prevented this same farm from being used in 2019, so an alternative alluvial soil field (49 ha) was selected near Salisbury, MO (39.3326˚ lat., –92.9239˚ long.). Though also in close proximity to the Missouri River, it was unaffected by flood waters. Within this field, using the cooperator's 24-row planter, 16 ha of the 49-ha field was used for this study. Each plot consisted of 24 rows, each 1,000 m long with 76-cm row spacing. The planter was equipped with the same planter technology as the four-row planter. Due to the inability of the planter to maintain the 7.6-cm planting depth, only three depths (3.8, 5.1, and 6.4 cm) were included. Each planting depth was replicated three times in a randomized complete block design.

Planting at each of the two soil texture areas occurred on the same day in each of the experimental years. Soil conditions were adequate for corn planting as temperatures were >10 ˚C. Both soil texture areas had soybean [*Glycine max* (L.) Merr.] as the previous year's crop. In 2017 and 2018, the seedbed was tilled conventionally, but in 2019, there was no tillage. Immediately after planting in 2017 and 2018, a remote weather station was set up within 3 m of the study area border to capture growing conditions. Every 15 min, average air temperature and total precipitation were recorded. Air temperature readings after planting were used to calculate cumulative growing degree days (GDD). Additionally, a soil sensor network was installed immediately after planting to record seed-zone conditions in 2017 and 2018. The network included CS655 sensors, installed within each block at each planting depth and hard-wired to a data logger (Campbell Scientific). Soil temperature and volumetric water content were obtained every 15 min throughout the germination and emergence period. This temperature and water content was then averaged over three intervals of the germination period: 0–3, 4–10, and 11–15 d after planting. Due to the large scale of the site in 2019, it was not possible to set up the soil sensor network.

For this study, "germination" was the time from planting to emergence. "Germination period" refers to the time from planting to total emergence. All plant germination measurements were taken from two 3.0-m-long sections (1.5 m in 2017) from the two adjacent rows in the center of each plot. All plots were monitored daily for plant emergence over the entire germination period. Plants were considered emerged once the coleoptile or "spike" was visible at the soil surface. Each day, newly emerged plants were marked with a unique, colored plastic garden stake to differentiate the specific day of emergence. Emerged plant counts were recorded after the emergence period, which typically occurred at the V3 developmental growth stage.

Three response measurements were generated from the collected emergence data. First, corn emergence timeliness was evaluated based on emergence rate. This was measured as the days required from planting to 90% emergence of the planting rate. Second, the emergence window characterized uniformity of emergence. This response was measured by the days between the first emerging plant and an emerging plant that represented 90% of the planting rate emergence. Third, emergence percentage was a measure of emergence success and was calculated as the fraction of emerged seedlings from the total seed planting population. At the end of the growing season, all plants from the emergence tracking section (2.3 m^2 in

TABLE 1 Site characteristics for the soil texture and landscape position studies

	Soil texture study						Landscape position study					
	Coarse-textured soil			Fine-textured soil			Foot slope position		Back slope position		Summit position	
Characteristic	2017	2018	2019	2017	2018	2019	2018	2019	2018	2019	2018	2019
Soil series	Sarpy	Sarpy	Norborne	Peers	Peers	Tina	Leonard	Leonard	Leonard	Leonard	Leonard	Leonard
Hillslope component	Fluvial flood plain	Fluvial flood plain	Fluvial flood plain	Fluvial flood plain	Fluvial flood plain	Fluvial flood plain	Upland	Upland	Upland	Upland	Upland	Upland
Clay, %	6.7	3.6	15.6	26.9	19.7	24.7	18.5	18.1	24.5	23.3	18.5	29.7
Silt, %	20.3	3.5	16.5	45.8	41.0	27.4	76.2	76.9	69.2	70.9	76.2	64.9
Sand, %	73.0	92.9	67.9	27.3	39.3	47.9	5.3	5.0	6.3	5.8	5.3	5.4
Texture	Sandy loam	Sand	Sandy loam	Loam	Loam	Sandy clay loam	Silt loam	Silt loam	Silt loam	Silt loam	Silt loam	Silt loam
Drainage class	Well drained	Well drained	Well drained	Well drained	Well drained	Well drained	Poorly drained	Poorly drained	Poorly drained	Poorly drained	Poorly drained	Poorly drained
Organic matter, g kg^{-1}	1.3	0.6	1.75	2.1	2.0	2.5	2.0	2.64	2.2	2.67	2.3	2.99
Total C, g kg^{-1}	0.88	0.4	1.1	1.17	1.21	1.57	1.33	1.54	1.29	1.47	1.12	1.57
CEC[a], % base saturation	149	210	67	120	133	81	84	80	88	76	82	74

[a]CEC, cation exchange capacity.

2017 and 4.6 m^2 in 2018–2019) were harvested. All ears were harvested, dried, and final grain yield was calculated at 15.5 g kg^{-1} moisture.

2.2 | Landscape position study

Research was conducted on a claypan soil toposequence in 2018 and 2019 at the University of Missouri Bay Farm Research Facility near Columbia, MO (38.8809° lat., −92.2018° long.). Three landscape positions (summit, back slope, and foot slope) were identified within two adjacent fields for each of the study years using onsite evaluations and electrical conductivity to identify landscape positions similar in topsoil depth (Kitchen et al., 1999). All landscape positions from both years were mapped as a Leonard soil series (fine, smectitic, mesic Vertic Epiaqualfs; Soil Survey Staff, 2002).

Within each landscape position, four replications of four seeding depths (targeting 3.8, 5.1, 6.4, and 7.6 cm) were arranged in a randomized complete block design. This resulted in 16 plots per soil landscape position. Each plot consisted of four 9.1-m-long rows at 76-cm spacing. At planting, soil moisture and temperature conditions were considered suitable for corn germination. Planting occurred in no-till conditions with soybean residue from the previous growing season.

For this study, daily temperature and precipitation data were obtained from a remote weather station that was located within 2 km of the research site at the University of Missouri Bradford Research Center. As with the other study, CS655 sensors (Campbell Scientific) were used for soil temperature and soil moisture measurements. All other measurements were the same as the soil texture study.

2.3 | Data analysis

Data analysis was conducted by site-year for each study to examine emergence performance by planting depth. With these analyses the assumptions of normality and equal variance were met based on residual vs. predicted scatterplots. Dependent variables included emergence rate (days), emergence window (days), emergence percentage (%), and grain yield (Mg ha^{-1}) and the independent variable in all analyses was planting depth. Planting depth was considered a fixed effect and replicate and interactions between replication and planting depth were considered random. Data were analyzed at $\alpha = .1$ using the MIXED procedure of SAS (SAS Institute, 2006), and when significant means were separated using LSD differences at $\alpha = .1$.

Because soil textures and landscape positions could not be randomized or replicated, and the physical locations of the trials had to change each year so that corn was always planted into soybean residue for consistency, the texture or landscape factor could not be included in the statistical analysis. However, since weather, seed genetics, past management, and research treatments were constant within study and year, we attribute differences primarily to texture or landscape position factors for *these* research sites (i.e., no generalization to other fields). These comparisons document examples of seed emergence performance differences between similarly managed fields in close proximity to each other, or even between areas of the same field, but that differ in soil conditions.

TABLE 2 Analysis of variance for corn establishment characteristics from 2017 to 2019 at the soil texture study and landscape position study sites

	P > *F*			
Study	Emergence rate	Emergence window	Emergence %	Yield
Soil texture study				
Coarse 2017	NS[†]	NS	NS	NS
Fine 2017	.066	.066	NS	.084
Coarse 2018	NS	NS	NS	NS
Fine 2018	.018	<.01	NS	NS
Coarse 2019	NS	NS	<.01	NS
Fine 2019	NS	NS	NS	NS
Landscape position study				
Summit 2018	<.01	.029	NS	NS
Back slope 2018	<.01	NS	NS	NS
Foot slope 2018	.047	.047	NS	NS
Summit 2019	.011	NS	NS	NS
Back slope 2019	.020	NS	NS	NS
Foot slope 2019	<.01	NS	NS	–

[†]NS, not significant.

3 | RESULTS AND DISCUSSION

3.1 | Soil texture study

3.1.1 | Stand establishment

Emergence rate (days to 90% emergence) was affected by planting depth (Table 2), but not the same by study location (i.e., soil texture). The type and magnitude of response was weather dependent. Similar trends were evident among sites within the same year; therefore, weather-induced conditions interacted with planting depth and affected emergence rate.

Emergence rate was relatively fast in 2017 compared with the next two years (Figure 1a). Warm temperatures leading up to and after planting in 2017 best explain the rapid emergence for this year (Table 3). In 2017, the average daily air temperature of the first 3 d after planting was 21 ˚C,

TABLE 3 Weather and soil temperature measurements for three different windows of days after planting (0–3, 4–10, and 11–15 d), shown for each site-year. Average and minimum soil temperature were obtained at two depths (3.8 and 7.6 cm)

	Precipitation			Avg. air temp.			Avg. soil temp.						Min. soil temp.					
							0–3 d		4–10 d		11–15 d		0–3 d		4–10 d		11–15 d	
Field	**0–3 d**	**4–10 d**	**11–15 d**	**0–3 d**	**4–10 d**	**11–15 d**	**3.8 cm**	**7.6 cm**	**3.8 cm**	**7.6 cm**	**3.8 cm**	**7.6 cm**	**3.8 cm**	**7.6 cm**	**3.8 cm**	**7.6 cm**	**3.8 cm**	**7.6 cm**
Soil texture study	mm			°C														
Coarse 2017	0	10	21	21	17	14	22	21	19	19	17	17	19	18	13	10	12	11
Fine 2017	0	10	21	21	17	14	22	21	19	19	16	16	19	18	13	10	12	11
Coarse 2018	0	0	8	5	11	14	12	12	15	15	19	19	4	6	9	10	10	12
Fine 2018	0	0	8	5	11	14	11	11	15	14	19	18	4	6	9	10	10	12
Coarse 2019	8	1	2	14	14	17	–	–	–	–	–	–	–	–	–	–	–	–
Fine 2019	8	1	2	14	14	17	–	–	–	–	–	–	–	–	–	–	–	–
Landscape position study																		
Summit 2018	0	8	0	11	17	18	14	14	18	18	21	21	8	10	10	11	9	10
Back slope 2018	0	8	0	11	17	18	14	14	18	18	21	21	8	10	10	11	9	10
Foot slope 2018	0	8	0	11	17	18	14	14	18	18	21	21	8	10	10	11	9	10
Summit 2019	0	8	1	14	10	13	14	13	13	13	16	15	6	6	4	5	4	6
Back slope 2019	0	8	1	14	10	13	14	13	13	13	16	15	6	6	4	5	4	6
Foot slope 2019	0	8	1	14	10	13	14	13	13	13	16	15	6	6	4	5	4	6

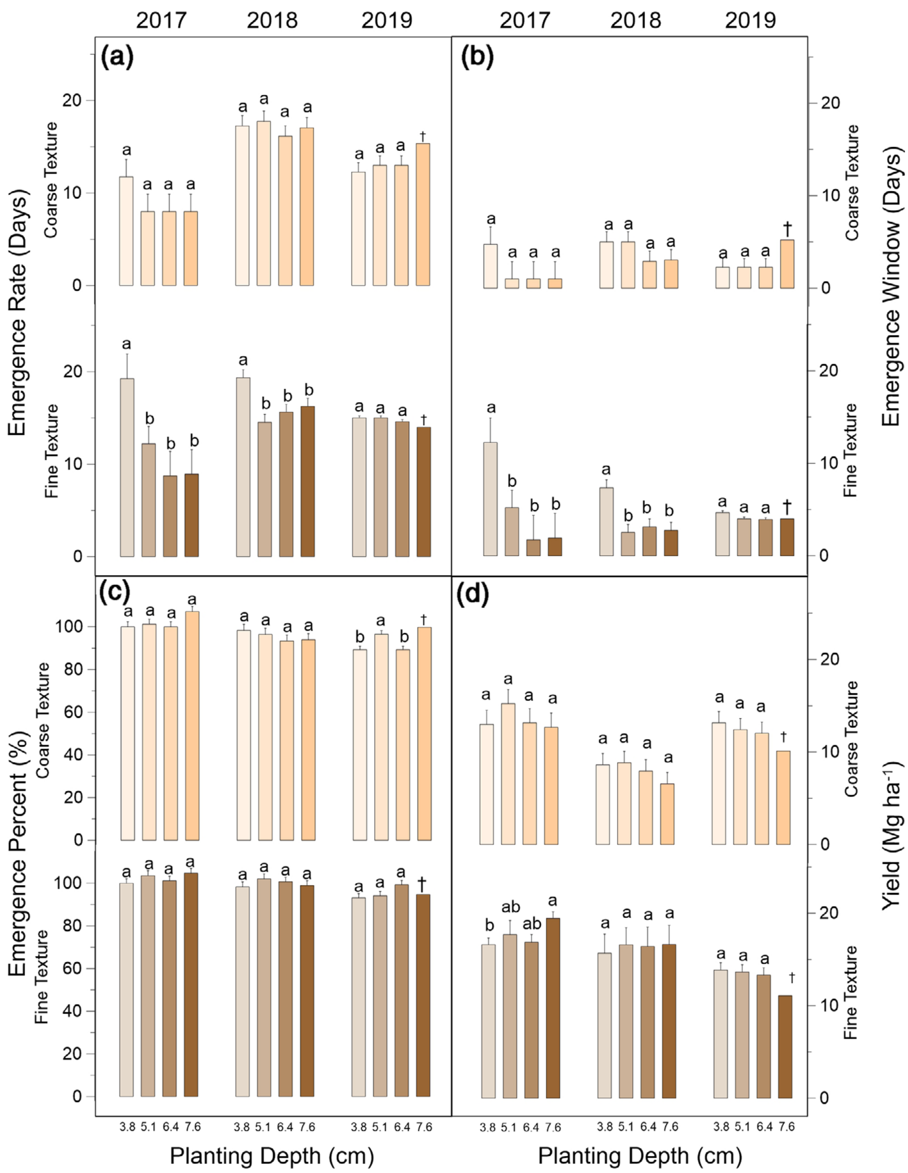

FIGURE 1 Emergence rate, window, percentage, and grain yield for three growing seasons by texture and planting depth. Differences ($P \leq .1$) between planting depth within year and soil texture are shown with lowercase letters. Emergence rate is measured as days from planting to 90% emergence. Emergence window is measured as days from first emerged plant to 90% emergence. Emergence percentage is the percentage emerged from target seeding rate. †The 7.6-cm planting depth was not replicated in 2019, so this depth was excluded from statistical analysis

substantially higher than the same 3 d in 2018 and 2019 (5 and 14 ˚C, respectively). Emergence rate for the study locations in 2017 was 2.5 d quicker, on average, than the other 2 yr.

Planting depth affected emergence rate at two of the six study locations: the fine texture locations in 2017 and 2018. For these two fine-textured sites, the shallowest-planted seed (3.8 cm) experienced a delayed emergence rate in both years compared with deeper depths. In 2017, seed planted at the three deeper depths on the fine-textured soil had an emergence rate between 8 and 12 d, but the shallow depth required an additional 8 d to reach 90% emergence. Though planted in moist soil, slower emergence with shallow seed was attributed to poor seed-to-soil contact. Observations noted larger soil "clods" that could have produced air voids in the immediate seed zone for shallow planted seed, even after the planter press wheels closed the seed trench. This was not an issue for the deeper planting depths. Additionally, more crop residues were observed within the seed trench for the shallow seed depth. The combination of these two factors likely reduced seed-to-soil contact, and therefore likely produced water limitations to germinating seeds (see Figure 2 for 2017) during warm and dry days after planting (Table 3). We attribute this as the cause of slower emergence rate for shallow seed in fine-textured soils. The response in 2018 was similar, and likely for the same reasons. The delay with shallow-planted seed was

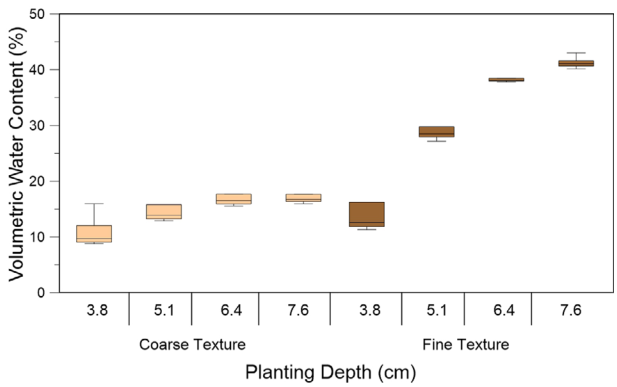

FIGURE 2 Daily average of volumetric water content over first 15 d from planting in 2017

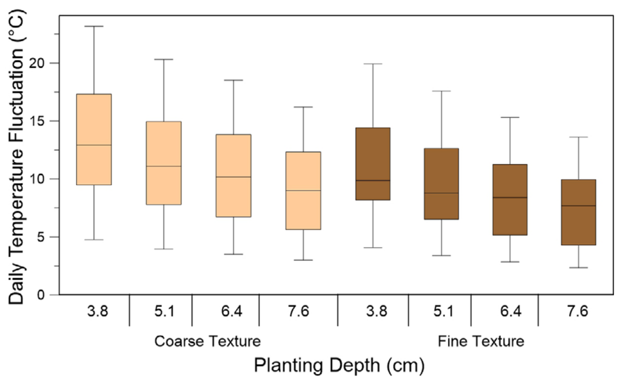

FIGURE 3 Average daily soil temperature fluctuations at four planting depths in 2017

less than in 2017, probably because milder air and soil temperatures followed planting (Table 3).

When contrasting emergence rate within a year but across the site-years of this research (assumed primarily to be a soil texture effect), differences only occurred for fine textured soils (Figure 1a, 2017 and 2018). Here, emergence rate was slower with shallow planted seed on fine-textured soils. One explanation is the seed-to-soil contact issue described previously, which was not observed for the coarse-textured soil. Additionally, although average daily soil temperatures were similar for both textures, greater daily temperature fluctuations in the coarse soil led to warmer daytime temperatures and more rapid emergence (Figure 3).

Generally, warm conditions promote rapid corn emergence provided there is sufficient moisture available to the seed (Stoll & Saab, 2014). Ensuring rapid emergence is generally desirable, as it lengthens the potential growing season, decreases time when the seedling is most vulnerable and dependent on seed reserves, and encourages uniform stands (Hoeft et al., 2000). Although rapid emergence is desirable, disparity in moisture or temperature at a given depth can slow emergence (Hadas, 2004). Maintaining rapid emergence requires attention to seedbed conditions to ensure both temperature and moisture are suitable. These results reinforce the need to consider temperature forecasts and potential soil drying in the days immediately after planting to make better-informed planting depth decisions.

Uniformity of emergence, as measured by emergence window, produced findings similar to emergence rate (Figure 1b). Within the fine-textured soil in 2 of 3 yr, emergence window differed by planting depth. When compared with deeper planting, the shallowest-planted seed extended the emergence window an average of 9 d in 2017 and 4 d in 2018. This effect was also attributed to issues causing poor seed-to-soil contact at the shallow depth. As with emergence rate, the impact was greater when germination conditions were warmer (i.e., 2017).

Uniformity for all 3 yr was poorest at the 3.8-cm planting depth when examining effects across all site-years. Nemergut (2021) also reported increased emergence uniformity with seeding depths greater than 3.8 cm, and this was related to lower soil moisture and warmer soil temperatures at shallow depths. Lack of uniform emergence creates greater plant-to-plant competition and the potential for yield loss (Maddonni & Otegui, 2006; Nemergut et al., 2021). This response with shallow planting depths on fine-textured soil prompts need for increased attention to improve emergence uniformity as planting progresses from field to field or across variable fields from coarse-texture soil into finer-textured soil with heavy plant residue. This demonstrates that for highly variable soil fields like the one in this study, variable seeding depth adjustments may be justified in certain years and textures, especially when weather conditions near planting are less than ideal.

Emergence percentage was rarely different between planting depths (Figure 1c). Corn seed is resilient, and given sufficient time and suitable germination conditions, seedlings will often emerge despite stresses that cause delays. The cause of differences between planting depths for the 2019 coarse-textured soil is unclear. In 2017 and 2018, emergence exceeding 100% was the result of a relatively high number of "double" planted seeds. In a few comparisons, a slightly lower emergence percentage was observed with coarse-textured soil than fine-textured soil. Over all 3 yr, the average emergence percentage was 97.1% for coarse-textured soil and 99.2% for fine-textured soil.

3.1.2 | Grain yield

For the fine-textured soil in 2017, planting at the 3.8-cm depth reduced grain yield by 2.8 Mg ha^{-1} compared with the deepest planting depth (Table 2, Figure 1d); otherwise, yield was not affected by planting depth. We attribute this yield loss to the emergence rate and uniformity challenges during stand establishment previously described. Planting depth stand establishment differences may or may not influence final yield. In this study with contrasting soil textures, there were few instances for which stand loss occurred and delayed plants likely still were able to contribute to harvestable grain yield. There may have been compensatory effects for plants that emerged earlier than others (i.e., ears per plant, rows per ear, kernels per row, kernel weight; Nafziger et al., 1991; Nemergut et al., 2021). Many studies have documented that yield differences in response to planting depth and stand are site specific (Coronel et al., 2020; Cox & Cherney, 2015; Poncet et al., 2019; Thomason et al., 2008). Typically, many factors in conjunction with planting depth affect yield differences, including growing season, row-unit downforce, and plant populations (Poncet et al., 2019). Under the conditions of our study, yield loss was associated with shallow planting on fine-textured soil that exhibited significant clods, followed by warm and dry weather. Nemergut et al. (2021) also found that under warm soil conditions, yield increases as planting depth increased were more likely for a higher organic matter field than for a low organic matter field.

Grain yield in 2017 and 2018 was generally higher with fine-textured soils than for coarse-textured soils. We attribute yield differences between these two soil textures of these sites to soil productivity differences. For these 2 yr, the fine-textured soil generally had much greater clay content (Table 1) and therefore higher water holding capacity (~40 cm for profile) compared with the coarse-textured soil (~11 cm for the profile: Soil Survey Staff, 2002). Because the coarse-textured soil had such a low water holding capacity, periods of crop water stress on these soils are commonly observed. Another property noticeably different for the 2017 and 2018 sites was soil organic matter (Table 1). Fine-textured soil had about twice the soil organic matter of the coarse-textured soils. The positive role of soil organic matter on productivity has been extensively documented (Bauer & Black, 1994). These two soil differences help explain the yield decrease on the coarse-textured soils for these years. For 2019, the two soil texture sites were not nearly as contrasting (Table 1), and yield was equivalent.

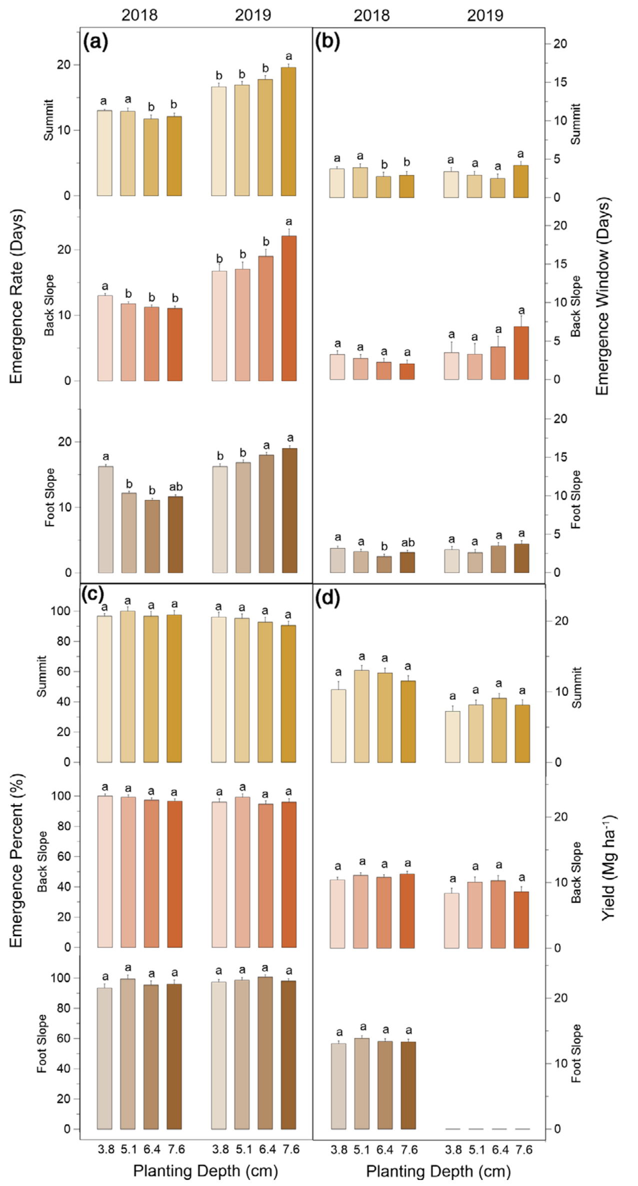

FIGURE 4 Emergence rate, window, percentage, and grain for two growing seasons by landscape position and planting depth. Differences ($P = .1$) between planting depth within year and soil texture are shown with lowercase letters. Emergence rate is measured as days from planting to 90% emergence. Emergence window is measured as days from first emerged plant to 90% emergence. Emergence percentage is the percentage emerged from target seeding rate

3.2 | Landscape position study

3.2.1 | Stand establishment

For all three landscapes positions in both years, planting depth influenced emergence rate (Table 2; Figure 4a); however, response differed uniquely by conditions during germination and emergence (Table 3). In 2018, deeply planted seed generally emerged more quickly across all landscape positions. On average across the landscape positions, the emergence rate of the two deepest planted seed depths was about one day ahead of the shallowest depth (Figure 4a). This response between planting depths was more dramatic at the foot slope position, with slowest emergence rate at the shallow planting depth. Since average soil temperatures were equivalent across landscape positions (Table 3), we presume when contrasting the landscape positions of these sites that emergence response was caused by soil moisture differences (visual observations only).

For 2019, an opposite trend was observed. Here, under much cooler conditions than 2018 (Table 3; see Days 4–15), emergence rate was considerably slower (averaged six more days than 2018). Under these cooler conditions, emergence rate was quickest with shallower planting and was similar over all three landscape positions. Compared with the two shallowest depths, the emergence rate was delayed an average of 3.5 d for the deepest planted seed (i.e., 7.6 cm). For this site-year, deep planting on the back slope position slowed emergence rate the most with an additional 2.8 d to reach 90% emergence. Often in claypan soil fields topsoil thickness at the back slope position has been reduced by erosion to less than 10 cm (Nikiforoff & Drosdoff, 1943). With high argillic soil near to or even mixed into the seed zone, soil warming will often be slowed as the heat capacity of high-clay-content soil is greater (Wang et al., 2019). The same condition could result in near-surface poor internal drainage, resulting in excessive moisture in the seed zone environment. For this study, we observed stunted root development from unearthed seeds adjacent to the plots. For high-clay soils known to warm and dry more slowly in the springtime, cold weather conditions can greatly impair corn germination and emergence (Schneider & Gupta, 1985). Under these conditions and based on our findings, planting shallow (i.e., 3.8- to 5.1-cm depth range) would be recommended.

Uniformity of corn emergence for 2018 generally followed the same pattern as emergence rate (Table 2; Figure 4b). Stands that emerged more rapidly were more uniform. In general, uniformity of emergence was slightly higher for the back and foot slope positions (~1 d) than the summit. Under the cooler germination conditions of 2019, emergence uniformity was not significantly influenced by planting depth, though the trend was for less uniformity with the deepest planting.

Final emergence percentage (Figure 4c) was not affected by planting depth at any landscape position for either study year (Table 2). This response demonstrates that over a range of temperature and moisture conditions, given sufficient time, most corn seeds will germinate and emerge. Regardless of the final emergence, and as previously discussed, a uniform corn stand that has not emerged quickly and uniformly may result in yield loss. In 2019, planting at the two deepest depths at the summit position generally resulted in fewer plants (~7%) compared with the foot slope. Although emergence percentage performance by planting depth is minimal within a specific landscape position, comparing varying moisture, temperature, and plant residues at specific depths across a field may prompt planting depth adjustments.

3.2.2 | Grain yield

Within growing season, grain yield for each landscape position was similar for all planting depths (Figure 4d). As discussed above, planting depth that leads to stand establishment differences may result in similar yield because of the compensatory effect of other yield components. Although planting depths yielded the same within landscape position, numerical differences were observed for these study sites when contrasting across landscape positions (Figure 4d). In 2018, the foot slope generally yielded more than the other landscape positions. Corn yield variation on claypan soil landscapes often tracks topsoil thickness (i.e., more topsoil, more yield; Conway et al., 2017), best explained by variation in potential plant available water between landscape positions. Trends across landscape positions were driven by growing season differences in rainfall distribution. In 2018, dry weather around pollination most affected the back slope position.

In 2019, summit and back slope position yields were generally similar.

4 | CONCLUSIONS

Corn seed is quite resilient when planted near recommended (~3.8 to 5.1 cm) depths and will normally germinate and emerge quickly with suitable moisture and temperature conditions. However, as this research demonstrated, those conditions may be less than ideal because of year-specific weather altering site-specific soil environments within fields. This was the primary reason for exploring the influences of corn planting depth on stand establishment and yield over multiple years, soil textures, and landscape positions. On alluvial soil, deep planting (7.6 cm) often resulted in the most uniform and timely emergence. Shallow planting (3.8 cm) gave the least uniform emergence and was particularly troublesome on fine-textured soil under warm conditions. Under these warm and dry conditions, poor emergence performance with shallow planting translated into lost grain yield, but only on the fine-textured soil where seed-to-soil contact was less than ideal. On claypan soil landscapes, stand establishment showed contrasting trends. When warm, deep planting depths provided enhanced emergence uniformity and rate, whereas the opposite was true for cool conditions. For the landscape position study, however, emergence differences from planting depth did not affect grain yield as other factors, such as soil water availability to plants, had greater impacts on yield than stand establishment.

When comparing the three emergence performance metrics used in these studies, the findings of emergence rate and emergence uniformity were often similar. Emergence rate and uniformity were expected to track each other as seeds that germinate and emerge quickly suggest ideal planting conditions, and therefore more uniform emergence between plants. Final emergence percentage rarely varied by planting depth. This demonstrates that, given sufficient time to germinate and emerge, modern corn hybrids are hardy over a range of temperature and moisture conditions.

Collective results from the soil texture and landscape studies support the concept that certain soil textures and landscape positions require greater attention to achieve optimum stand establishment, particularly when weather conditions near planting are not ideal. This research examined a single planting date into often moderate conditions; additional research assessing a range of planting dates within a single year and conditions is needed. In this study, planting depth affected stand establishment by slowing and reducing uniformity, but rarely altered emergence percentage. Additional planting depth research into more extreme planting conditions may expose scenarios where there is a larger impact on emergence success. When conditions vary within fields or adjacent fields managed similarly, variable planting depth actions could be performed manually or integrated into on-the-go planter prescriptions. Forecasted weather during the emergence period may also be needed for such prescriptions. These results also demonstrate that despite early establishment differences, stands can often compensate and maintain similar yield potential.

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AUTHOR CONTRIBUTIONS

Stirling Stewart: Conceptualization; Data curation; Formal analysis; Writing-original draft; Writing-review & editing. Newell Kitchen: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Supervision; Writing-review & editing. Matt Yost: Conceptualization; Data curation; Investigation; Methodology; Project administration; Supervision; Writing-review & editing. Lance Stephen Conway: Data curation; Investigation; Methodology; Writing-original draft; Writing-review & editing. Paul Carter: Conceptualization; Funding acquisition; Resources; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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