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Row-crop planter performance to support variable-rate seeding of maize

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Abstract

Current planting technology possesses the ability to increase crop productivity and improve field efficiency by precisely metering and placing crop seeds. Planter performance depends on determining and utilizing optimal settings for different planting variables such as seed depth, down pressure, and seed metering unit. The evolution of "Big Data" in agriculture today brings focus on the need for quality as-planted and yield mapping data. Therefore, an investigation was conducted to evaluate the performance of current planting technology for accurate placement of seeds while understanding the accuracy of as-planted data. Two studies consisting of two different setups on a 6-row, John Deere planter for seeding of maize (*Zea mays* L.) were conducted. The first study aimed at assessing planter performance at 2 depth settings (25 and 51 mm) and four different down pressure settings (varying from none to high), while the second study focused on evaluating planter performance during variable-rate seeding with treatments consisting of two seed metering units (John Deere Standard and Precision Planting's eSet setups) with five different seeding rates and four ground speed treatments which provided a combination of 20 different meter speeds. Field data collection consisted of measuring plant emergence, plant population and seed depth whereas plant spacing, plant population after emergence along with distance and location for rate changes within the field were also recorded for the variable-rate seeding study. Results indicated that both depth setting and downforce affected final seeding depth. Measured seed depth was significantly different from the target depth even though time was spent adjusting the units to achieve the desired prior to planting. Crop emergence did not vary significantly for the different depth and downforce settings except for target depth in Field 1. Results from the variable-rate study indicated that seeding rate changes were accomplished within a quick response time (< 1 s) at all ground speeds regardless of magnitude of rate change. Data showed that planter performance in terms of emergence and plant spacing CV was comparable for most of the meter speeds (17.4–33.5 rpm) among the two seed meters utilized in the study. Plant spacing CV increased with an increase in meter speed, however no significant differences existed among meter speeds in the range of 17.4–33.5 rpm. Results implied that correct seed metering unit setup is very critical to obtain expected performance of today's planting technology. A concerning find was that the quality of as-applied maps from the commercial variable-rate display was not reflective of the actual planter performance in the field. The study recommended that operators need

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to ensure the correct planter and display setups in order to achieve needed seed placement performance to support variable-rate seeding.

Keywords Variable-rate · Planter performance · Seed metering · Downforce · Seed depth · Maize

Introduction

Today, farmers are charged with maximizing crop yields to provide for the growing world population while using inputs in a judicious manner to maintain profitability. During the 1990s, costs of agricultural inputs started to increase plus a need for environmental stewardship materialized requiring US farmers to develop more efficient and sustainable management strategies. At the same time, the availability of the global positioning system (GPS) to civilians commenced the evolution of what is now known as precision agriculture (PA). GPS-based guidance along with yield mapping were the initial technologies being adopted on farms with variable-rate technology (VRT) following shortly thereafter. Since that time, these technologies have become standard options on farm equipment. Many row-crop planters come equipped with hydraulic drives and associated in-cab display enabling farmers to implement variable-rate seeding (VRS), if interested. With VRS capabilities in-house coupled with rising seed costs and inherent in-field variability, interest is high among US farmers to take advantage of this VRT as a means to manage risks and maintain profitability.

Here in the US, maize (*Zea mays* L.) continues to be the largest planted crop with about 85 to 95 million acres planted from 2008 through 2014 (USDA NASS 2014). Planting constitutes one of the most important, if not most critical, field operations within a growing season for maize. Correct seeding population and seed placement during planting is important since these influence uniformity of emergence, crop development and yield potential (Morrison and Gerik 1985; Wanjura 1982). Mistakes at planting will have an effect over the entire growing season for maize; in most cases a negative impact. A seed requires absorption of soil moisture for germination (Hunter and Erickson 1952) with soil moisture within the seed bed most affecting the timing of germination and 1st emergence. Favorable planting conditions and optimum planting performances are required for proper germination of the crop and to maximize yield potential (Carter et al. 1989). Emergence in maize can be defined as the stage where the seed has germinated and starts coming out of the ground. It is commonly known throughout the US Corn Belt that uniform emergence is required to maximize yield potential. Past research has also highlighted the importance of early and uniform emergence to attain a high yielding crop (Ford and Hicks 1992; Nielson 1993; Staggenborg et al. 2004; Yagzi and Degirmencioglu 2007). Planting requires opening of the soil, commonly termed as the furrow, to desired depth followed by placement of seeds in the opened furrow then closing of this furrow (Moody et al. 2003) using press wheels mounted on the planter. However, completion of these steps is usually not sufficient to result in good uniform emergence of seeds, especially in the Southeast US where high soil variability (e.g. differences in soil type, texture, etc.) can exist within a same field. Numerous factors including non-ideal field conditions at planting, varying weather conditions during growing season, and negligence towards planter setup and operation affect the quality of seed emergence, making it really difficult to achieve a uniform emergence in maize in the Southeast US. Factors most often mentioned in literature affecting crop emergence are soil properties (e.g. texture and moisture content at planting; Srivastava et al. 2006), depth of the furrow in which seeds are dropped, downforce (defined as the amount of pressure exerted by the planter gauge wheels on to the soil; Hanna et al. 2010) and planter performance (Nielsen 1994). Considering the highly variable soils in the Southeast US, the ability to consistently place seeds at the desired depth while maintaining the target population and seed spacing can be challenging. Current, PA displays and VRT capabilities have provided the ability to precisely monitor planter performance in real-time. However, an important aspect is the quality of the as-planted data and its ability to accurately reflect the placement of seed in the field.

A major PA topic here in the US and worldwide is “Big Data” and how it will evolve in agriculture. While data management and Farm Management Software packages have been around since the mid-1990s, more US farmers are interested in archiving farm generated data off machines and using it to derive information which can be used to support management decisions (Fulton et al. 2013); data-driven decision is commonly the term to describe this process. The development of a VRS program for maize at the farm level requires several ingredients including the correct PA technology but also an understanding of the growing environment on a field-by-field basis. This understanding not only requires farmer intuition but spatial data layers as well to create management zones (MZ) in which each zone has a unique seeding rate. Common spatial layers for development of seeding MZs include a soil map, elevation data, and yield maps. Within the agriculture industry, yield and as-planted maps are becoming more important as these two data layers serve to understand implementation of a VRS program and the ability to evaluate it in terms of benefits for an individual field (Jeschke et al. 2015). The absence of one of these layers makes it difficult to truly evaluate and understand VRS, and can potentially create false-positive results for a farmer. One assumption of any data layer is its quality. Poor quality data leads to erroneous results and ultimately incorrect decisions. In particular, these data must be of quality to define the appropriate MZs for VRS of maize since MZs tend to be dynamic or be revised over a few years as more data is collected and requires understanding of what in-field environmental aspects are driving yield. Past research has indicated quality concerns on as-applied maps and their ability to truly reflect the spatial performance of a machine equipped with VRT (Fulton et al. 2003, 2012; Virk et al. 2013). Therefore, an important component of Big Data success in agriculture relies on both the technology being adopted by farmers and the quality of spatial data layers so the analytics being developed can generate information which farmers can use in their decision process.

This study was conducted to provide a better understanding of the current capabilities of implementing VRS of maize in the Southeast US. In particular, interest in VRS of maize are increasing as observed by the increasing number of VRS services being offered by seed companies and 3rd party precision ag data management companies. As-planted data in conjunction with yield maps is needed to ensure correct evaluation and fine-tuning of zone management to support VRS. The authors hypothesized that a high planter performance for accurate seed placement in conjunction with an accurate spatial depiction of planting parameters is required of the current planting technology for successful adoption of VRS. The main objective of this study was to verify the current field performance of the planting technology for accurate seed placement while understanding the accuracy of as-planted data in depicting actual planter performance. The specific objectives of the study were (1) to assess planter performance at different depth and downforce settings by measuring seed depth and emergence attained in the field, and (2) to examine current planting technology (seed metering unit, variable-rate controller and display) in achieving desired field performance during a VRS operation.

Materials and methods

The study was conducted at the E.V Smith Research Center (Shorter, AL, USA) during the 2014 growing season. Real-time Kinematic (RTK) is the primary GPS correction being used on all PA technology at this research farm. This study used a 6-row, John Deere integral row-crop planter with MaxEmerge row units. The planter row-units were configured with standard shark-tooth wheels as row cleaners and a set of solid rubber closing wheels mounted behind the opener discs. The settings for row-cleaners and closing wheels were based on the prevalent soil conditions in the selected fields. The row-units on the planter toolbar were arranged at a row-spacing of 91 cm. Heavy duty down pressure springs were used on each row-unit that nominally provide no additional down force or can be positioned to exert 0.45, 1.11 or 1.78 kN (referred to as none, low, medium and high, respectively) of additional down force per row (John Deere product literature, John Deere, Moline, IL, USA). Depth control is managed using a T-handle adjustment that controls stop height for the gauge wheels on each row unit. A Trimble Rawson hydraulic control system (Trimble Inc., Sunnyvale, CA, US) provided the variable-rate capabilities for the planter and was operated using the Trimble Field IQ technology. A John Deere 8130 row-crop tractor equipped with a Trimble Auto-Pilot system using VRS (virtual reference station) as the RTK correction source. The tractor was used to pull the strip-till equipment and planter. A Trimble FMX display with variable-rate and by-row seed monitoring functionality was used for all tests. A Precision Planting 20/20 SeedSense Seeding display and FieldView (Precision Planting LLC, Tremont, IL, US) product were also used to monitor all seeding parameters. Each seed tube had a Dickey-John high-rate seed sensor (Dickey-John Corp., Auburn, IL, US) mounted on it to provide feedback to both the Trimble and Precision Planting technologies. Prior to planting, all fields were strip-tilled.

A planter specific data acquisition system was developed within the Biosystems Engineering department for monitoring and logging real-time planting parameters. These parameters included actual meter speed and row unit acceleration/vibration data spatially tagged using a differential global positioning system (DGPS) receiver in order to create spatial data for analyses. Meter speed was determined using a 3600 pulse per revolution encoder (TRD-GK, Koyo Electronics Industries Co., Kodaira-shi, Tokyo, Japan). A Raven Industries Phoenix 200 DGPS receiver (Raven Industries, Sioux Falls, SD, US) was mounted on the planter along the centerline of the row-units. This data acquisition system was developed using a National Instruments LabView program and a National Instruments USB 6225 DAQ board (National Instruments, Austin, TX, US) with a 10 Hz sampling frequency used. A user interface was developed to monitor all planting data during field operation on a laptop. Data collected from this system was used to generate an as-planted map representing the true planting population in the field.

Three fields were selected to conduct two unique planter performance experiments. The first experiment consisted of assessing planter performance at 2 depths (25 and 51 mm) and four different down pressure settings (varying from none to high) for a total of eight treatment combinations. A uniform seeding rate of 65200 seeds ha^{-1}, and a constant ground speed of 7.0 km h^{-1} with Precision Planting eSet meter setup were used for all treatments. Two fields with different but known soil properties were selected; Field 1 was a sandy-silt loam while Field 2 was a clay-loam. Planting depth and downforce (same as down pressure) settings were the factors selected as main treatments in this study. Initial planting depth was established by adjusting the T-handle for depth settings on the planter based on manually exposing planted seeds within buffer rows using the 1.11 kN setting. Once the 25 and 51 mm planter depth settings were established, they were used for each field. For each field, all treatments were replicated four times. Each replication contained all eight treatments (Fig. 1) and represented a differentiated area of the field. The experiment was implemented where each planter pass represented an individual treatment and the treatments were randomly placed within each replication (Fig. 1). The colored strips represent layout of planter passes within first replication in Fig. 1. The experimental design was based on a randomized block design where each combination of a seed depth and downforce was randomly assigned to a strip with a total of eight randomized treatments within each replication. Each strip was six planter rows wide (5.5 m) and approximately 485 m in length. Data collection was organized along a grid and determination of sampling site was established by drawing six transects across each field (Fig. 1). Data were collected at the intersection between these transects and each pass which represented a total of 192 sampling sites.

The following data was collected at each sampling site: soil moisture content at planting, stand counts after full emergence, and actual planting depth. Soil moisture content was collected at planting using a HydraProbe sensor (Stevens Water Monitoring Systems Inc., Portland, Oregon, US) at each sampling site and consisted of one data point at each location. Stand counts were performed in 7.6 m section randomly selected within each crop row at the sampling site. Percent of emerged plants was computed by dividing the population

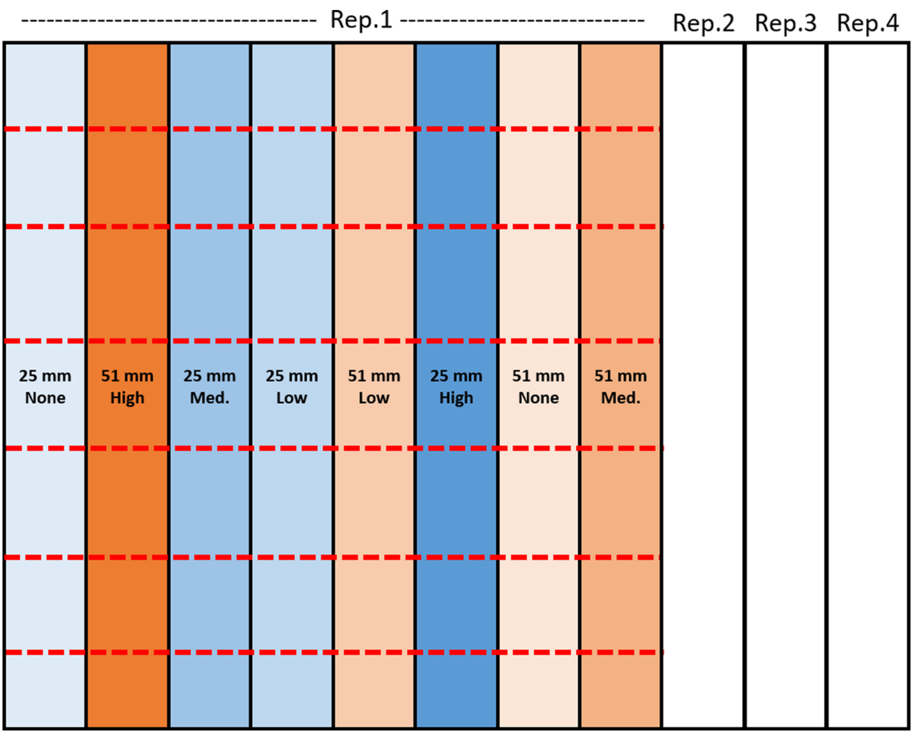

Fig. 1 Field 2 layout for the seeding depth by downforce experiment illustrating the eight different treatment combinations within first replication and the six transects (red lines) representing sampling sites for each plot. Each strip (different color) in the map represents an individual planter pass consisting of a combination of a seed depth and a downforce treatment. Each treatment was replicated four times within the field in the similar randomized manner as shown in first replication (Color figure online)

counts by the target seeding rate in seeds per hectare. Actual planting depth was measured after planting, once the maize reached the V1 to V2 growing stage. The methodology consisted of extracting a total of 10 randomly selected individual seedlings (total of 10 from all four rows) from the soil within the same 7.6 m section at each sampling site and measuring the distance between the center of the seed and the soil surface. This measurement was identified as the actual planting depth of maize versus target seed depth for analysis.

The second experiment, conducted in Field 3, focused on evaluating planter performance during VRS with treatments consisting of two seed metering units (John Deere Standard and Precision Planting's eSet) with five different seeding rates (49400, 59300, 69200, 79100 and 89000 seeds ha^{-1}) and four ground speed treatments (6.1, 7.1, 8.2 and 9.4 km h^{-1}) for a total of 20 treatments with each seed meter. A single planter pass represented an individual ground speed treatment (main treatment) with seeding rates varied (split treatment) within the ground speed. Seeding prescription (Rx) maps were generated in AgLeader's SMS Advanced software (AgLeader Technology, Ames, IA, US) and exported for the appropriate display type. Figure 2 presents the Rx map with seeding rates randomized in the same order within each replication. All treatments were randomized and replicated four times for a total of 20 treatments. The trial was implemented as a strip-split

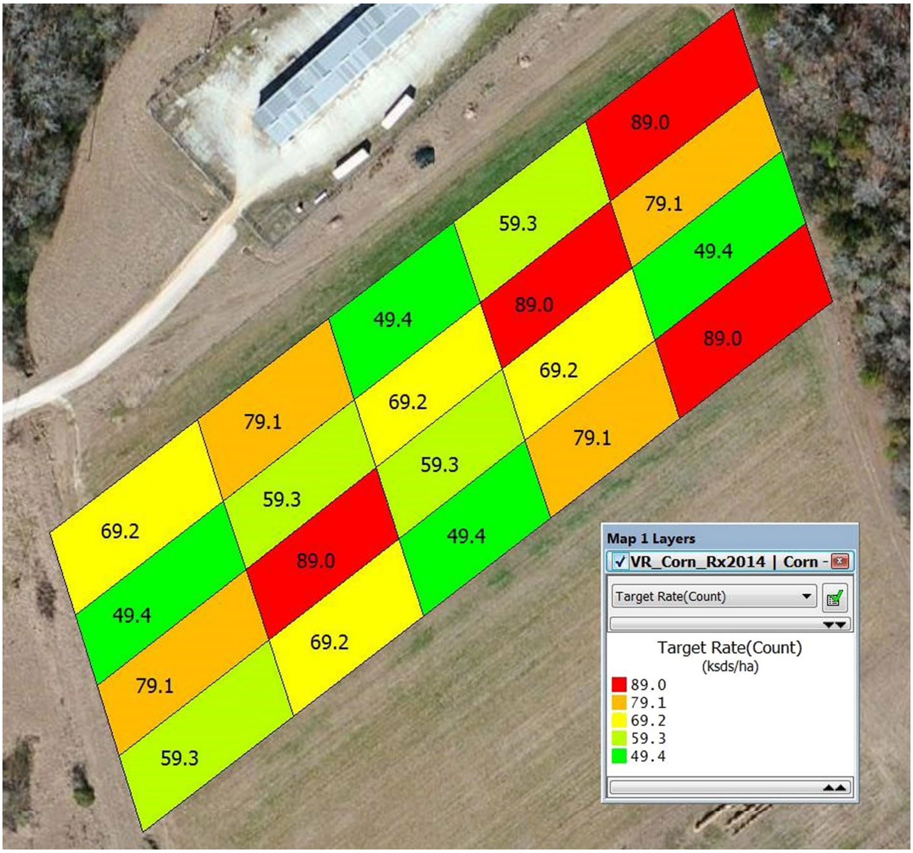

Fig. 2 Maize prescription (Rx) map illustrating seeding rate (units are 1000 seeds ha^{-1}) by replication for Field 3. Ground speed treatments were randomized within each replication and constituted one planter pass

plot design in the field. The plots were 5.5 m wide (single 6-row planter pass) and 53.3 m in length. The treatments were implemented by achieving the desired ground speed before entering the plots and maintaining the same ground speed while planting all seeding rate treatments within that strip. Further, seed meter speed (in revolutions per minute; rpm) corresponding to the different ground speed and seeding rate combinations was computed (Table 1) using a row spacing of 94 cm, as meter speed is a function of ground speed, seeding rate, and row spacing. At the center of each plot, plant spacing data was collected on the four middle rows (rows 2 and 3 for John Deere Standard meter, and rows 3 and 4 for eSet meter) after emergence by measuring the plant-to-plant spacing for 50 consecutive plants in each row. The outside two rows (rows 1 and 6) were left as a buffer in each plot. The total distance for these 50 consecutive plants in each row was recorded, and the plant population (plants ha^{-1}) for each row was calculated by dividing 50 plants with the computed area (measured distance × row width). Percent crop emergence was computed by dividing the measured plant population by the target seeding rate within each plot. The mean plant spacing and standard deviation was used to calculate coefficient of variation (CV %) to assess the plant spacing uniformity within the treatments. A low CV value represents a uniform plant spacing and is mostly desirable for planting row-crops. In the region within each pass where the seeding rate transition occurred, the location (documented using a GPS handheld device) with the length over the four center rows for a rate change was measured using a tape measure to the nearest 0.25 cm. Since ground speed was constant per pass, these distance measurements were converted to a time for a rate change to occur. As-planted data consisting of plant population was also recorded using

Table 1 Summary of meter speeds (in rpm) corresponding to different ground speed and seeding rates (based on row spacing of 91 cm)

Ground speed (km h^{-1})	Target rate (seeds ha^{-1})	Meter speed (rpm)
6.1	49400	15.4
	59300	18.5
	69200	21.6
	79100	24.6
	89000	27.7
7.1	49400	17.8
	59300	21.4
	69200	25.0
	79100	28.5
	89000	32.1
8.2	49400	20.7
	59300	24.8
	69200	28.9
	79100	33.1
	89000	37.2
9.5	49400	23.9
	59300	28.7
	69200	33.5
	79100	38.2
	89000	43.0

the available VR display in the tractor for both studies and analyzed for comparing planter performance based on actual field data.

All data was summarized in Microsoft Excel. For first experiment, target seeding depth and downforce were treated as main treatment variables, and crop emergence and measured seed depth were treated as response variables. A two-way analysis of variance (ANOVA) was conducted using a statistical analysis software SAS (SAS Institute, Cary, NC, US) to determine the effect of main treatments on response variables, and if any interaction existed among the main treatments. For second experiment, meter speed in revolutions per minute (rpm) was used as a treatment variable for one-way ANOVA analysis with percent emergence and CV as the response variables. Since meter speed is a function of ground speed and seeding rate which were implemented in a strip-split plot design in the field, appropriate error terms considering this experimental design were utilized during statistical analysis. The transition time data collected during VR study was also analyzed using ANOVA analysis with ground speed and seeding rate as the main treatments, and transition time as the response variable. All statistical comparisons were made at the 95% significance level with an alpha value of 0.05.

Results and discussion

Seeding depth and downforce study

The first study focused on planter downforce and seeding depth offered insight to how these two planter settings affect final seeding depth. It should be remembered that on traditional row-crop planters, these parameters are usually set once and not changed by the operator for an entire field or several fields. Typically these parameters are only changed during planting if field conditions significantly change. Table 2 provides a summary of overall mean soil moisture content, seeding depth and emergence for Fields 1 and 2. Statistical analysis indicated significant differences in soil moisture content ($p < .0001$), seeding depth ($< .0001$) and emergence ($p = 0.0270$) values between Fields 1 and 2. Differences in moisture content values for Fields 1and 2 indicated a considerable moisture variability between the two fields. Field 1 was relatively dry as exhibited by low soil moisture content than Field 2. Data showed that Field 1 tended to be planted little shallower than Field 2 as the seeding depth (39 mm) obtained in Field 2 was relatively deeper than seeding depth (35 mm) in Field 2. This could be attributed to the moisture variability between the two fields as a shallow seed depth can be expected in dry soil conditions with similar planter setup. Overall variation in seeding depth was relatively small across each field with standard deviations of 7 mm or less. The overall mean crop emergence between the two fields

Table 2 Overall mean soil moisture content, seeding depth, and emergence for Fields 1 and 2

Field	Moisture content (%)	Measured seeding depth (mm)	Emergence (%)
1	15^{b} (4)	35^{b} (7)	95^{b} (5)
2	26^{a} (5)	39^{a} (5)	96^{a} (4)

Values in parenthesis represents standard deviation

Values with same letters within a column are not significantly different ($\alpha = 0.05$)

Table 3 ANOVA analysis results showing p-values for seeding depth and emergence for main effects of depth, downforce and their interaction for Fields 1 and 2

Field	Test effects	Seeding depth	Emergence
1	Target depth	< .0001	< .0001
	Downforce	0.0094	0.2650
	Depth × downforce	0.4394	0.1298
2	Target depth	< .0001	0.4123
	Downforce	0.0129	0.0765
	Depth × downforce	0.2643	0.0685

Table 4 Summary of mean seeding depth and emergence values for main treatments (seeding depth and downforce) for Fields 1 and 2

Treatment	Levels	Field 1		Field 2	
		Seeding depth (mm)	Emergence (%)	Seeding depth (mm)	Emergence (%)
Seeding depth (mm)	25	32^{b} (7)	93^{b}	37^{b} (5)	96^{a}
	51	39^{a} (5)	97^{a}	41^{a} (5)	96^{a}
Downforce settings	None	33^{b} (6)	94^{a}	37^{b} (5)	96^{a}
	Low	36^{a} (8)	95^{a}	39^{a} (6)	95^{a}
	Medium	36^{a} (7)	95^{a}	40^{a} (5)	96^{a}
	High	37^{a} (8)	96^{a}	40^{a} (5)	97^{a}

Values in parenthesis for seeding depth represents standard deviation in mm

Values with same letters within a column are not significantly different ($\alpha = 0.05$)

was significantly different, although Field 1 exhibited only 1% lower emergence than Field 2. The 95–96% crop emergence was considerably good for the soil types in these fields but lower than past studies focused on maize that mostly emerged between 96% and 99%. The low standard deviations between 4 and 5% for emergence in both fields indicated fairly uniform emergence across each field.

The results from ANOVA analysis for main effects of target depth, downforce, and depth × downforce interaction for Fields 1 and 2 are presented in Table 3. Statistical analysis showed that final planting depth was significantly affected ($p < .0001$) by the seed depth and downforce in both fields. Emergence was significantly different for the target seeding depths in Field 1 but not in Field 2. For both fields, downforce had no significant effect ($p > 0.05$) on emergence. The depth × downforce interaction was determined to be non-significant ($p > 0.05$) and did not affect final seeding depth and emergence in Fields 1 and 2. Table 4 presents the summary of mean final seeding depth and emergence values by each main treatment (target depth and downforce) separately for Fields 1 and 2. For both fields, the final seeding depth tended to be deeper for the target seeding depth of 25 mm and shallower for the target seeding depth of 51 mm. For Field 1, the emergence (93%) attained at 25 mm seeding depth was significantly lower than the emergence (97%) achieved at 51 mm seeding depth suggesting a decrease in crop emergence at shallower planting depth in this field. The mean emergence achieved in Field 2 was 96% for both seeding depths of 25 and 51 mm. For both fields, the final seeding depth tended to increase with applied downforce with deeper seeding depths attained at high downforce settings. However, statistical analysis showed significant differences in seeding depth existed only between none downforce treatment and all other downforce treatments. Although such a low or no downforce is typically not used by growers for planting maize in the Southeastern US, however the impact of downforce on planting depth especially at lower downforce values indicate a minimum downforce requirement (between zero and low) for planting maize where large variations in seeding depth can be expected in the field if not maintained above that minimum value. The final seeding depth was not significantly different between the downforce settings of low, medium and high suggesting no effect of downforce on seeding depth at these downforce treatments. For Field 1, the emergence seemed to increase with an increase in downforce but no significant differences existed between the emergence values at different downforce settings. The emergence differed between the low and high downforce for Field 2 with high downforce exhibiting higher overall emergence of 97%, though the emergence values were not statistically different from each other. This could be explained by the fact that higher downforce may have provided better seed to soil contact for the soil type and prevalent soil conditions in this field which favored higher seedling emergence.

In summary, both depth and downforce settings significantly influenced final planting depth but results from this study implied the difficulty of maintaining the target seeding depth in maize when using only one depth and down force setting. The results can further vary considerably depending on the amount of soil variability present within the field. An additional result from Field 1 and 2 data included that one of the primary factors driving emergence was soil moisture content. Further, the presence of large in-field soil moisture variability has the potential to affect crop emergence along with influence due to improper selection of depth and downforce during planting. This information reinforces the need to not only understand processes in play at planting time but develop technologies that would enable to better manage this variability and improve planting performance. The ability to place seeds at the target planting depth and at the correct population ensures that maximum or near maximum yield potential exists from day 1 when seeds are placed in the ground.

Variable-rate seeding study

The ANOVA analysis results for VR seeding study indicated that plant spacing varied significantly ($p < .0001$) for the different meter speeds for both John Deere Standard and Precision Planting eSet meter (Table 5). This result was expected as plant spacing was influenced by seeding rate which impacts meter speed. For PP eSet meter, CV was significantly ($p = 0.0021$) affected by the meter speed whereas meter speed did not influence CV for JD Standard meter. Statistical analysis also indicated no significant differences ($p > 0.05$) in crop emergence for different meter speeds indicating no effect of meter speed on emergence for both seed meters. Table 6 presents the summary of mean plant spacing, CV, and emergence for different meter speeds attained during the field tests. The measured plant spacing was within 2–13 mm of the target spacing for the JD Standard meter, and within 2–11 mm for the Precision Planting eSet seed meter. The measured plant spacing differed between the meter speeds due to the fact that

Table 5 ANOVA analysis results showing p-values for seed spacing, CV and emergence with meter speed as the main effect

Seed meter	Main effect	Plant spacing	CV	Emergence
JD standard	Meter speed	< .0001	0.0959	0.1698
PP eSet	Meter speed	< .0001	0.0021	0.2152

Table 6 Summary of plant spacing, coefficient of variation (CV %), and crop emergence (%) by meter speed for both John Deere Standard and Precision Planting eSet Metering units

Meter speed (rpm)	Target spacing (mm)	John deere standard			Precision planting eSet		
		Plant spacing (mm)	CV (%)	Emergence (%)	Seed spacing (mm)	CV (%)	Emergence (%)
15.4	221	227^{ab}	26.1^{a}	98^{a}	227^{a}	21.2^{b}	97^{a}
17.8	221	226^{ab}	27.1^{a}	98^{a}	227^{a}	22.7^{ab}	97^{a}
18.5	184	188^{c}	29.6^{a}	98^{a}	195^{b}	29.8^{ab}	94^{a}
20.7	221	231^{a}	27.9^{a}	96^{a}	229^{a}	25.8^{ab}	97^{a}
21.4	184	190^{c}	26.8^{a}	97^{a}	193^{b}	27.2^{ab}	96^{a}
21.6	158	163^{d}	29.1^{a}	97^{a}	165^{c}	26.8^{ab}	96^{a}
23.9	221	223^{b}	26.2^{a}	99^{a}	229^{a}	29.2^{ab}	97^{a}
24.6	138	141^{e}	28.0^{a}	98^{a}	144^{d}	27.4^{ab}	96^{a}
24.8	184	191^{c}	29.5^{a}	96^{a}	193^{b}	25.8^{ab}	96^{a}
25.0	158	163^{d}	31.2^{a}	97^{a}	164^{c}	26.8^{ab}	97^{a}
27.7	123	129^{e}	33.3^{a}	96^{a}	130^{e}	32.6^{a}	94^{a}
28.5	138	145^{e}	31.6^{a}	96^{a}	145^{d}	30.7^{ab}	96^{a}
28.7	184	190^{c}	31.5^{a}	98^{a}	195^{b}	30.0^{ab}	95^{a}
28.9	158	169^{d}	37.8^{a}	94^{a}	162^{c}	26.3^{ab}	98^{a}
32.1	123	129^{f}	34.0^{a}	95^{a}	130^{e}	31.1^{ab}	94^{a}
33.1	138	142^{e}	30.4^{a}	97^{a}	146^{d}	30.0^{ab}	95^{a}
33.5	158	171^{d}	36.1^{a}	93^{a}	164^{c}	24.7^{ab}	96^{a}
37.2	123	129^{f}	34.8^{a}	95^{a}	131^{e}	33.3^{a}	94^{a}
38.2	138	145^{e}	34.7^{a}	96^{a}	147^{d}	33.8^{a}	95^{a}
43.0	123	130^{f}	36.4^{a}	94^{a}	131^{e}	32.9^{a}	94^{a}

Values with same letters within a column are not significantly different ($\alpha = 0.05$)

meter speed is a function of seeding rate and ground speed, and any changes in seeding rate affects the target seed spacing at the given ground speed. For both seed meters, the overall trend observed was that the CV values increased with an increase in meter speed, however no significant differences existed between the CV values at different meter speeds for the John Deere Standard meter. The computed CV values for Precision Planting eSet were, on average, lower than the CV values for the John Deere Standard. The CV values were 31.2% or higher for meter speeds above 25 rpm for John Deere Standard meter setup with a maximum of 36.4% above this rpm. The CV for the eSet meters was only higher than 31% for meter speeds above 28.5 rpm with a maximum of 33.8%. For Precision Planting eSet meter, the CV values observed at meter speeds of 27.7, 37.2, 38.2, and 43.0 rpm were significantly differently from the CV attained at lowest meter speed of 15.4 rpm. This result indicated that the plant spacing uniformity degraded with an in increase in meter speed for the selected meter speeds. Lab testing of these meter units on a meter test stand prior to planting demonstrated that meter performance can degrade sharply at higher meter speeds (> 38 rpm) for both meter setups. The overall crop emergence for both seed meters ranged from 93% to 99% with some of the lowest emergence values (93–95%) observed at the meter speeds of 32.1, 37.2 and 43.0 rpm for both seed meters. Both seed meters provided very comparable emergence with no particular trend observed in emergence values with an increase in meter speed.

Table 7 Mean time for seeding rate transition for each ground speed

Ground speed (km h^{-1})	Rate transition time[a] (s)
6.1	1.0[a] (0.2)
7.1	0.9[a] (0.2)
8.2	0.7[a] (0.1)
9.5	0.8[a] (0.2)

Values in parentheses represent standard deviation in s

[a]Values with same letters are not significantly different (α = 0.05)

Table 8 Mean time for seeding rate transition based on the magnitude of the rate transition

Magnitude in rate transition increment / decrement (seeds ha^{-1})	– 39540	– 29650	– 19770	– 9880	9880	19770	29650	39540
	Rate transition time (s)							
Mean (SD)	1.0[a] (0.2)	0.8[a] (0.2)	0.8[a] (0.2)	0.8[a] (0.2)	1.0[a] (0.2)	0.9[a] (0.1)	0.8[a] (0.2)	0.7[a] (0.1)

Positive rate transition values indicate an increase in rate whereas negative represent a decrease. Values in parentheses represent standard deviation in s

Values with same letters are not significantly different (α = 0.05)

Results indicated that the plant spacing uniformity and emergence was not affected by meter speed for both seed meters with the exception of CV values at the lowest meter speed (15.4) and three high meter speeds (37.2, 38.2 and 43.0) for Precision Planting eSet meter.

The VRS results in Field 3 revealed the distance to make a seeding rate change (e.g. transition distance) was 2.0 m or less regardless of the magnitude in the rate change. Converting the distance values to seconds indicated the response time for the variable-rate system for making seeding rate transitions was close to 1.0 s or less irrespective of the ground speed. No significant difference was found between the rate transition times for each ground speed (Table 7). The only small trend observed was that the rate transition time decreased at higher ground speeds which makes sense since the distance measured in the field for a rate transition was consistent among different ground speed treatments. Observing the magnitude of rate increments or decrements at the management zone boundaries (Table 8), the transition time was very consistent (0.7–1.0 s) irrespective of the rate change magnitude. Data showed no effect of ground speed and the magnitude of the rate transition (whether increasing or decreasing) on the transition time. This indicated that the VRS technology used in the study was considered quick and consistent. This feature is highly desirable in a VR planter since a quick response time minimizes rate change errors between management zones.

For as-planted data comparison, two figures were generated to point out differences between actual planted data versus prescription map (Fig. 3) and the as-planted map generated by the VR display (Fig. 4). One note of the actual as-planted data (Figs. 3b, 4b) is that no VR seeding was performed during first pass due to operator error, therefore the data from first pass was omitted for this analysis. Comparison of the as-planted data in Fig. 3 revealed that a delay existed between when a rate transition occurred and the boundary of the management zone. The direction of travel, East-to-West versus West-to-East, generated

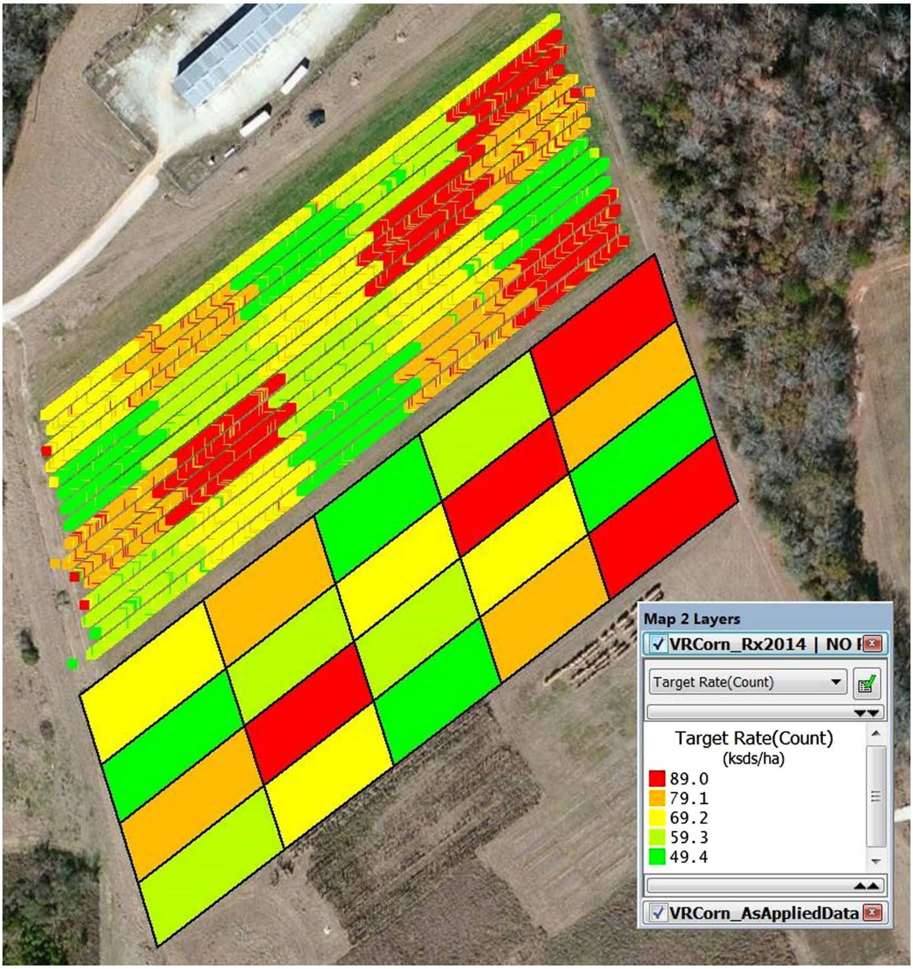

Fig. 3 Side-by-side comparison between (**a**) the prescription (Rx) map and (**b**) the actual as-planted map generated by data acquisition system. Seeding rate units in 1000 seeds ha^{-1}

different delay distances with the West-to-East being about half. The average delay distance West-to-East passes was 3.8 m with a maximum of 5.5 m at one transition while the East-to-West was on average 7.7 m and a maximum of 13 m. During an individual pass, the delay distance was consistent. This delay can be corrected with the look-ahead feature within the display but must be known to the operator in order to set it up precisely. The as-planted map (Fig. 4b) generated from data acquisition supports the above results in a quick rate transition (abrupt color changes) versus the display generated map (Fig. 4a). Comparison between the Rx and Actual as-planted map (Fig. 3) indicates that once a target population was achieved by the VRS technology, performance was good for at least meeting the target population until the next rate transition occurred. Differences also existed between the estimated applied or planted population in some areas. However, while global trends existed between the actual and display as-planted maps (similar color regions between the two maps) as observed in Fig. 4, illustrated differences between these layers indicated that

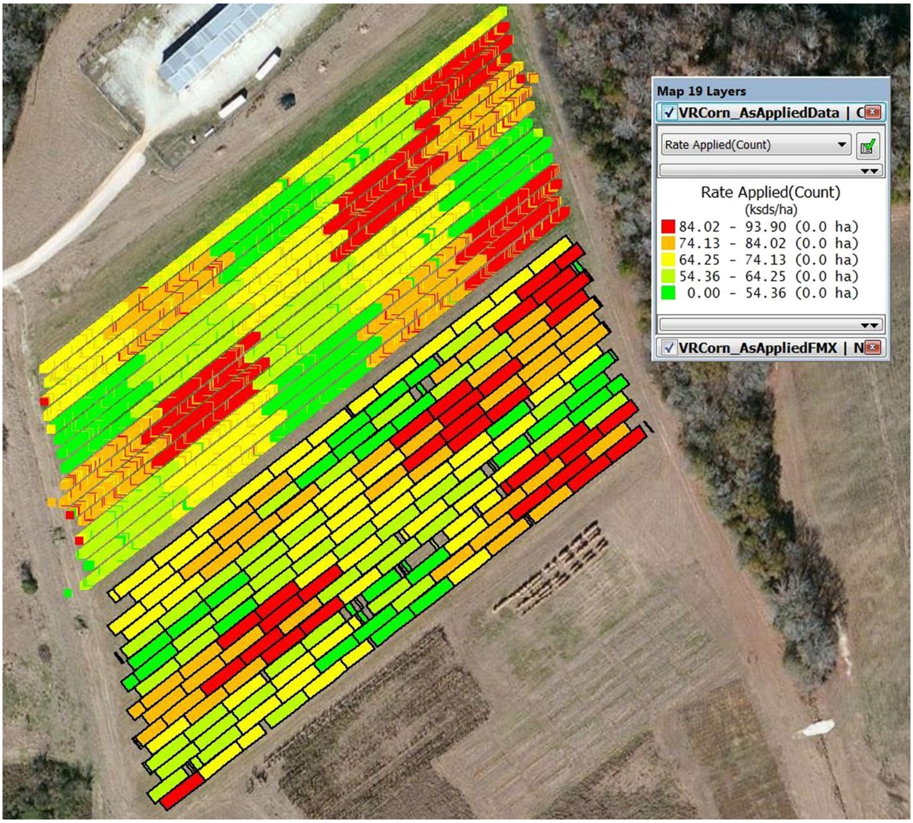

Fig. 4 Side-by-side comparison between (**a**) as-planted data generated by the in-cab VR display (polygon representation) and (**b**) the actual as-planted map generated by the data acquisition system (point representation). Seeding rate units are 1000 seeds ha^{-1}

the polygon representations were averaged values. This is a concern because while global trends (highs and lows) in estimated planted population tended to exist, the map does not provide true spatial detail on population of planter performance as reflected in the actual as-planted map. It was noted that neither of the as-planted maps (Figs. 3b, 4b) provided in-depth details on when rate transitions actually occurred indicating that these maps were not reflective of the actual planting (rates) in the field making it difficult to make any setup or on-the-go adjustments within the VRS technology. Therefore, disparity existed between display feedback and the resulting as-planted data which most likely was due to the averaging routines and spatial representation (e.g. polygon) within the VRS technology. Further investigation is needed to understand the quality of as-planted data generated by other displays but these results emphasize that more detailed high-resolution maps are required to implement and support VRS. Quality as-planted data reflecting notable details of planter performance will be most needed on the planting equipment for VR seeding applications, especially in areas where in-field soil variability can be considerable.

In summary, while these experiments only represent one growing season, they highlight the impact of adjustable planter parameters that influence final population, plant spacing, and ultimately plant emergence. These parameters need to be carefully considered within a VRS program since planter performance is important to implement this type of seeding strategy. Results suggested the difficulty in using only one planter setup across varying soil types to maintain a target seeding depth in maize, and resulted in seeding depth variations within the same field. Actual planting depth was affected by the planter depth setting and downforce which makes sense but difficult to manage by operators when moving between fields or especially within an individual field. The absence of detail to these parameters can cause seeding rate errors, variations in seeding depth and deviation in seed spacing within seeding zones thereby negating the purpose of VRS and ability to properly evaluate a VRS program. Incorporation of variable seed depth technology on newer planting machinery in near future necessitates that desired seeding depth is maintained with none to minimum variations by ensuring correct depth and downforce setting and by performing field verification of these settings. Variable-rate technology has improved over the years with technology available to implement quick rate changes today. This study indicated quick response time of the rate controller for making rate transitions whereas display as-applied map showed a delayed transitions at the management zone boundaries which was different depending upon the direction of travel. This difference can be corrected through use of the look-ahead feature within the in-cab display setup in order to shift the rate change to the management zone boundary. Although planter performance through current PA displays providing real-time population, singulation and other planting parameters, has helped to improve the quality of planting in the Southeast US. However, PA practitioners and seed companies providing VRS services must be aware of the correct planter and technology setup, and most importantly its limitations, to ensure success of implementation but also proper evaluation. The quality of as-planted data is vital as the Big Data evolution develops in agriculture. Results of this study highlight the need for improvement in as-planted data layers so they accurately reflect in-field seeding parameters such as final population. It may be necessary that as-planted data provide more information than just population to support VRS in maize here in the Southeast US due to high in-field variability. Quality of as-planted data is needed as farmers rely on data management services to help drive decisions about input and machine management. Accurately documenting factors which influence emergence such as seeding rate, seed spacing and depth through as-planted data would help to ensure that proper decisions are made when evaluating VRS or other on-farm trials related to maize.

Conclusions

The study aimed at investigating the in-field planter performance for accurate placement of seeds, and to achieve desired seed spacing and target plant population to support the VRS of maize with current planting technology. Timely and uniform crop emergence, low seed depth variations, high plant spacing uniformity, quick rate transitions, and a detailed as-planted map reflective of true field application are all indicators of high planter performance in the field, and are highly desired of current planting technology for performing VRS. Results from this investigation indicated that final seeding depth of maize was impacted by both the planter depth setting and downforce applied on the gauge wheels. Final seeding depth varied significantly from the target depth for both Fields 1 and 2 used in the study. For both fields, the final seeding depth was deeper than the target seeding depth of 25 mm whereas the final seeding depth was shallower for the target seeding depth of 51 mm. Crop emergence was affected by target seeding depth in Field 1 but no such effect on emergence was observed for both depth and downforce in Field 2. Crop emergence was significantly different between the two seeding depths in Field 1 but not in Field 2. The crop emergence ranged from 94% to 97% for both the fields irrespective of the downforce treatments. In Field 3, where VRS was implemented, the transition time between rate changes was less than 1.0 s regardless of the magnitude in the rate change. No trends existed for the seeding rate transition time with both ground speed and seeding rate indicating quick and consistent performance of the VRT used on this planter. However, a delay or lag was observed during a rate change when crossing a management zone boundary, which varied with the travel direction. The average delay was 7.7 m when traveling East-to-West versus 3.8 m for West-to-East. Therefore, the correct planter and display setups must be used including defining the GPS location relative to the seed meter and entering the right look-ahead time within the display. Improper setup can impact final maize population and rate changes can initiate before or after the preferred MZ boundary. The two different seed metering units utilized in the VR study provided comparable performance in terms of seed spacing, CV and emergence at different meter speeds. The plant spacing CV increased with an increase in meter speed but no significant effect of meter speed on CV and emergence was observed for both seed meters with an exception of CV value at the lowest meter speed of 15.4 rpm and values at meter speeds of 37.2, 38.2 and 43.0 rpm for Precision Planting eSet meter. The emergence values ranged from 94 to 99% for the John Deere Standard, and from 94 to 98% for the Precision Planting eSet meter. Though the impact of meter speed on plant spacing uniformity was not statistically validated in the study, the quality of seed metering can degrade regardless of meter type at higher meter speeds with this aspect not clearly indicated at times in the as-planted maps. The study hypothesized that the current planting technology must provide detailed spatial maps representing actual planting parameters in the field. However, the as-planted maps from the two commercial systems provided general representation of the planter population across the field but did not reflect the correct location of rate changes and take into consideration the actual planter performance in terms of planted population, seed depth or plant spacing. The study recommended that operators need to ensure the correct planter and display setups in order to achieve desired seed placement performance to support VRS. In conclusion, implementing VRS in maize needs to consider the setup of the VR planter and technology to maintain desired seeding depth and ensure correct final population, while as-planted data must be improved and possibly include other parameters such as downforce and seeding depth.

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