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Abstract

Timely and quality planting of soybean is important to achieve maximum yield potential. Wet spring soil conditions and rain frequently shorten the time for farmers to plant crops within optimal soil conditions. New planter technology has been introduced that enables farmers to plant their fields faster and more precisely than with traditional planters. Large plot field studies were conducted in Indiana from 2015 to 2017 to evaluate a high-speed planter at various planting speeds with multiple seeding rates on soybean. Seedling emergence, plant distribution, and final yield were evaluated. Three planting speeds [8, 12, and 16 kilometers per hour (kph)] and two seeding rates (222,000 and 321,000 seeds ha^{-1}) were included in all years, and an additional planting speed and seeding rate were included in 2016 (20 kph and 420,000 seeds ha^{-1}, respectively). Overall, planting speed did not impact soybean seedling emergence. Uniformity of plant spacing decreased slightly as the planting speed increased from 8 to 20 kph in 2016. Cool and wet conditions immediately after planting likely led to inconsistent emergence. Final grain yield was not affected by planting speeds or seeding rate except in 2017 when 12 kph planting speed yielded 0.25 Mg ha^{-1} higher than the other planting speeds. Increasing planting speed can be achieved without detrimentally affecting plant population, plant spacing, and yield in soybean.

1 | INTRODUCTION

Timely or early planting is important to maximize soybean [*Glycine max* (L.) Merr.] yield (Beatty et al., 1982; De Bruin & Pedersen, 2008b). Spring soil and adverse weather conditions frequently shorten the time window for farmers to plant crops within optimal soil conditions or at the appropriate time. Equipment manufacturers and technology providers have introduced new planter technologies in the last decade (e.g., multi-hybrid planting, high-speed planting, updated in-furrow nutrient/chemical delivery technology [e.g., AccuShot, FurrowJet], or planter weight management system just to name a few) to improve the performance of the planters. High-speed planter technology offered by several companies is one of these improvements, which offers faster planting without sacrificing uniform seed delivery to the seed furrow compared to previous planter technology. The improvement of planter performance at higher speeds is due to an active seed delivery system (e.g., seed is delivered by a brush belt instead of free fall through a seed tube) from the metering unit to the seed furrow and partially from improved seed metering mechanisms. Benefits from such technology can be present in many ways: (i) During cooler and/or wetter springs when planting windows are limited, planting at higher speed can increase planting progress and potentially

Abbreviations: kph, kilometer per hour; PAS, plant available spacing; rpm, rotation per minute.

minimize yield losses (e.g., accomplishing timely plantings instead of delayed plantings). When the threat of significant rain is looming increased planting speed could also mean that a farmer can complete planting before adverse weather conditions halt operation. (ii) Soybean planting can occur earlier because many farmers in the Midwest plant their soybean after the completion of corn (*Zea mays* L.) planting (e.g., corn planting will be shorter and switch over to soybean occurs at earlier date). (iii) Planting progress (e.g., ha h^{-1}) can be maintained with a smaller (narrower) high-speed planter compared to a wider planter equipped with conventional planter technology.

Traditional planters tend to increase spatial variability of plant spacing in corn with increased planting speed (Liu et al., 2004; Staggenborg et al., 2004). Nielsen (1995) warned of the possibility of significant yield losses in corn with increased planting speed due to increased plant-to-plant variability; however, the plant population, plant spacing variability, and grain yield responses were not consistent in multiple field scale trials when planting speed increased from 6.5 to 13 kph. Variability in plant spacing increased, and grain yield decreased in corn when planting speed increased from 6.5 to 13 kph (Rankin & Lauer, 2000). Similarly, increased meter speed (increased planting speed and/or increased seeding rate) resulted in lower emergence percentage and higher variation in plant spacing using a John Deere Standard (John Deere) and Precision Planter eSet metering system (Precision Planting) in corn at planting speed ranges of 6–9.5 kph and seeding rate ranges of 49,000–89,000 seeds ha^{-1} (Virk et al., 2020). The eSet metering unit had overall about 1% lower emergence percentage, but more uniform plant spacing distribution and higher yield compared to the standard metering system (Virk et al., 2020). In soybean, seed delivery accuracy declined (increased double planting, and decreased acceptable within-row plant spacing), and grain yield decreased as planting speed increased up to 9 kph with a drill and row planter in Brazil (Bortoli et al., 2021; Brandelero et al., 2015).

After the introduction of high-speed planter technology, the interest on planter performance increased, especially in corn, due to the potential of improving plant stand uniformity. Seeding rates typically range from 74,000 to 94,000 seeds ha^{-1} in corn, whereas in soybean, it ranges from 250,000 to 450,000 seeds ha^{-1}. More uniform spatial distribution would be expected at a lower seeding rate (corn) than at the higher rate (soybean). There is limited published information on planter performance with increasing planting speed, especially beyond 13 kph speed. Most research has focused on corn plant spacing and grain yield. To date, limited knowledge exists on agronomic evaluation using a high-speed planter in soybean.

The objectives of this study were to (i) determine if planting speed using high-speed technology impacted emerged plant spacing (seed distribution) and (ii) evaluate if soybean yield was influenced by planting speed when using high-speed planting technology.

Core Ideas

- Soybean planting speed can be increased without yield penalty with new planter technology.
- Variation in plant spacing increased up to 6% as planting speed doubled.
- Seedling emergence was not affected by planting speed.

2 | MATERIALS AND METHODS

2.1 | Field description and equipment

Field studies were conducted from 2015 to 2017 to evaluate an ExactEmerge 1775NT (John Deere) high-speed planter. The planter was equipped with a John Deere vacuum meter with bowl-shaped seed plates and a brush belt seed delivery system. The studies were located at the Purdue University Agricultural Centers in west–central and northwest Indiana. Field locations and the dominant soil types for each location are presented in Table 1.

The study included the combination of three planting speeds [8, 12, and 16 kph (5, 7.5, and 10 mph, respectively)] and two seeding rates [222,000 and 321,000 seeds ha^{-1} (90,000 and 130,000 seeds ac^{-1})] in each year. In addition, an extra planting speed [20 kph (12.5 mph)] and an extra seeding rate [420,000 seeds ha^{-1} (170,000 seeds ac^{-1})] treatments were included in 2016. There were a total of 6, 12, and 8 treatments in 2015, 2016, and 2017, respectively. Treatments were assigned in complete randomized block design with split-plot arrangement, with planting speed as the main plot and seeding rates as the subplots. The number of replications varied between years due to the number of treatments and the size and shape of the field; five, three, and four replications were in 2015, 2016, and 2017, respectively.

A 24-row planter was used in the study, and seeding rates were randomly assigned for half of the planter width. Therefore, each plot was 12 rows wide with 0.76 m row spacing, and the length of plots varied from 100 to 800 m depending on field dimensions. Prescription maps were created to control seeding rate for each half of the planter as it transitioned into the next main plot of planting speed (i.e., 222,000 seeds ha^{-1} on the left side of the planter at 5 kph, and on the right side of the planter at 7.5 kph). Planting dates and the planted soybean varieties are presented in Table 1.

TABLE 1 Field location, dominant soil types, planting date, and planted soybean variety in each year of the high-speed planter evaluation experiment.

Year	Location	Soil types	Planting date and soybean variety
2015	West Lafayette, IN, USA (40˚28′43″ N, 87˚0′4″ W)	Chalmers silty clay loam (*fine-silty, mixed, superactive, mesic Typic Endoaquolls*) Raub-Brenton complex (*fine-silty, mixed, superactive, mesic Aquic Argiudolls*)	May 24, 2015 Pioneer 93Y60
2016	Lafayette, IN, USA (40˚16′7″ N, 86˚52′36″ W)	Drummer silty clay loam (*fine-silty, mixed, superactive, mesic Typic Endoaquolls*), Throckmorton silt loam (*Fine-silty, mixed, superactive, mesic Mollic Oxyaquic Hapludalfs*)	April 19, 2016 Becks 366L4
2017	Lacrosse, IN, USA (41˚19′8″ N, 86˚48′47″ W)	Gilford fine sandy loam (*coarse-loamy, mixed, superactive, mesic Typic Endoaquolls*), Maumee loamy fine sand (*sandy, mixed, mesic Typic Endoaquolls*)	April 26, 2017 Pioneer 28T08

2.2 | Data collection

Two transects in each plot were randomly selected prior to seedling emergence beyond 50 m from the start of each pass (to ensure that the planter traveled at target planting speed). Within each transect, two rows of 3 m long section in the lower seeding rate and two rows of 2 m long sections in the higher seeding rate were selected and marked immediately following planting to evaluate emergence for a similar number of plants in each row. In 2015 and 2016, these sections were visited daily, and emerged plants were counted in each row. Soybean plants were considered emerged when the cotyledon was completely above the soil surface. Emergence rate was not collected in 2017 due to the travel distance to the research site (∼140 km). The day to reach the 25%, 50%, and 75% emergence rates was determined from the daily emergence counts (e.g., the day it reaches 25% of the total plants within an emergence section). Daily thermal unit accumulation (growing degree days) was derived from weather data, obtained from a nearby automated weather station operated by the Indiana State Climate Office using the method outlined by Gilmore and Rogers (1958) establishing 10˚C (50˚F) and 30˚C (86˚F) temperature thresholds. Recorded dates were converted into accumulated air thermal units ($GDU_{°C}$) from planting for the 25%, 50%, 75%, and 90% emergence rates for each monitored row.

Plant available spacing (PAS) was measured in the same sampling area that was used for emergence rating data collection. The distance between plants was measured in the section within each row, and PAS was calculated for each plant as the mean distance of respective neighbor plants on each side of the plant (e.g., PAS for plant #2 is half of the distance between plant #1 and plant #3; Figure S1). Frequency distribution of individual PASs was graphed by 1 cm increments for each of the treatments. Four additional parameters were also calculated to evaluate the planter singulation performance described by Kachman and Smith (1995); the parameters included multiple index (D), miss index (M), quality of feed index (A), and precision (C).

A theoretical PAS (PAS_{ref}) was calculated using the target seeding rate. Plants were classified into three groups depending on their PAS relative to the PAS_{ref}. The PASs associated with each of the groups are presented in Table 2. The calculated PAS values for PAS_{ref}, the 0.5 and 1.5 times PAS_{ref} for the respective seeding rates, are shown in Table S1. For each treatment, multiple index (D), miss index (M), the quality of feed index (A), and the precision (C) were calculated following the methods described in Table 2.

Early-season plant population was estimated based on the number of plants within the emergence rating and PAS measurement zones and from additional two adjacent; eight zones (4 in 2017) of the center and four rows were included in each plot. Prior to harvest, final stand count was also collected in all the selected zones where seedling emergence rating was evaluated, unless these sections were drowned out during the growing season. In the case of water-damaged zones, stand count was performed on the same two rows within the plot but outside of impacted area.

Plots were harvested using a John Deere S650 combine with a 6.1 m (20 ft) wide header, positioned on the center 8 rows of each 12-row plot. Yield maps were collected using an Ag Leader yield monitor (Ag Leader Technology, Inc.) that was calibrated following manufacturer's procedure for

TABLE 2 Plant spacing classification groups based on their plant available space (PAS) relative to the reference PAS (PAS_{ref}), and the calculation methods for multiple index (D), miss index (M), quality of feed index (A), and precision (C).

PAS groups	Plant spacing relative to PAS_{ref}	Planter quality metrics
Group 1	$<0.5 \times PAS_{ref}$	$D = \frac{\text{number of plants in Group 1}}{\text{total number of plants}}$
Group 2	$0.5–1.5 \times PAS_{ref}$	$M = \frac{\text{number of plants in Group 3}}{\text{total number of plants}}$
Group 3	$>1.5 \times PAS_{ref}$	$A = \frac{\text{number of plants in Group 2}}{\text{total number of plants}}$
		$C = \frac{\text{SD of Group 2}}{PAS_{ref}}$

Source: Calculation methods adapted from Kachman and Smith (1995).

calibration. Data points from within 20 m of both ends of each pass were deleted (end trimmed) to discard the grain ramp-up time in the combine. Yield data points that were outside of three standard deviations of mean yield, or where affected by the change of combine speed, were also removed before analysis; the reported yields were adjusted to 13% grain moisture content. Harvest dates were September 30, October 6, and September 26 in 2015, 2016, and 2017, respectively.

2.3 | Statistical analyses

Planting speed and seeding rates were considered fixed effects, whereas replications were random effects. The statistical analysis was conducted separately for each growing season due to the different number of treatments in each year. Statistical differences were considered at the $p = 0.05$ significance levels.

Mean and coefficient of variation (CV) of thermal unit requirements were calculated for each plot at the 25%, 50%, 75%, and 90% emergence rates. Then the analysis of variance (ANOVA) was carried out on the plot means and CVs for each emergence rating stages using PROC MIXED procedure in SAS 9.4 software package (SAS Inc.).

An ANOVA was conducted on the following parameters: mean, standard deviation (SD), and CV of PAS, multiples (D), miss (M), quality of feed (A), and precision indices (C), plant population (early-season and harvest), grain yield, and grain moisture content at harvest similarly as described for plant emergence.

Pairwise contrast was used for the subset of the 2017 data (including data with planting speeds 8 and 16 kph) to analyze planter performance for the 173,000 seeds ha^{-1} seeding rate for each of the measured parameters in that year.

The CV of PAS and precision index were plotted against the metering unit speed, and linear regression was completed using the PROC REG procedure in SAS 9.4 software package.

3 | RESULTS AND DISCUSSION

3.1 | Seedling emergence

The increased soil displacement during planting (Figure 1) at the higher planting speed has raised the concern if ‘planting depth’ or more precisely the amount of soil on top of the seed differed with the different planting speeds. Therefore, seedling emergence was monitored to evaluate seedling emergence timing, emergence rate, and its uniformity as Hamman et al. (2002) documented longer mean emergence time with deeper planted soybean seeds. The actual seeding depth for the different planting speeds was not measured in this study. Seedling emergence occurred sooner with the 12 and 16 kph planting speeds at the beginning of the emergence period (i.e., fewer $GDU_{°C}$—less time/and heat accumulation to reach 25% and 50% emergence rate) compared to the 8 kph planting speed in 2015 (Table 3). However, planting speed did not affect the emergence rate at the end of the emergence period (75% and 90% emergence rates). The 12 and 16 kph treatments resulted in about 4.5%–5% lower CV compared to the

TABLE 3 Planting speed and seeding rates effect on air heat unit accumulation from planting to reach 25%, 50%, and 75% emergence progresses and their coefficient of variation (CV) using the John Deere ExactEmerge 1775NT planter in Indiana.

		25% emergence		50% emergence		75% emergence		90% emergence	
Speed (kph)	**Seeding rate (seeds ha^{-1})**	**Mean ($GDU_{°C}$)**	**CV (%)**	**Mean ($GDU_{°C}$)**	**CV (%)**	**Mean ($GDU_{°C}$)**	**CV (%)**	**Mean ($GDU_{°C}$)**	**CV (%)**
2015									
8		73.6 a	13.0 a	82.3 a	8.4	92.1	9.4	108.0	12.8
12		67.6 b	8.5 b	76.8 b	9.6	87.9	9.7	104.4	16.3
16		66.5 b	7.9 b	75.7 b	10.9	88.1	8.9	107.2	15.0
	222,000	70.1	10.7	78.2	11.0	89.5	11.8 A	107.5	17.4 A
	321,000	68.3	8.9	78.4	8.4	89.2	6.8 B	105.6	12.0 B
$p < F$									
Planting speed		0.0006	0.017	0.011	0.42	0.16	0.94	0.69	0.56
Seeding rate		0.21	0.23	0.89	0.096	0.88	0.02	0.60	0.02
Speed × seeding rate		0.52	0.44	0.55	0.17	0.49	0.61	0.20	0.02
2016									
8		72.6	1.0	76.4	4.5	94.9	11.1	113.8	9.3
12		72.5	0.8	77.6	4.8	93.8	10.2	113.5	9.9
16		72.6	0.8	77.9	7.0	97.1	12.6	117.3	10.6
20		73.2	2.8	77.9	7.8	94.7	14.9	114.0	8.4
	222,000	73.2	2.2	78.5	7.8	98.9	10.1	117.2	11.1
	321,000	72.7	1.4	77.6	5.4	94.0	13.3	112.9	8.4
	420,000	72.3	0.4	76.3	4.8	92.5	12.3	113.9	9.2
$p < F$									
Planting speed		0.48	0.15	0.94	0.52	0.88	0.19	0.79	0.78
Seeding rate		0.11	0.11	0.65	0.39	0.20	0.44	0.49	0.55
Speed × seeding rate		0.047	0.03	0.63	0.68	0.78	0.09	0.31	0.57

Note: Different lowercase letters indicate statistical differences between different planting speeds within a growing season and within parameter column at $p = 0.05$. Different uppercase letters indicate statistical differences between different seeding rates within a growing season and within parameter column at $p = 0.05$.

FIGURE 1 Soil displacement with the John Deere ExactEmerge 1775NT planter at 8 kph (left side) and at 16 kph (right side) planting speed in 2015.

8 kph treatment at the 25% emergence rate averaged across seeding rates in 2015 (Table 3) indicating a more uniform seedling emergence. At 75% emergence progress, seedling emergence uniformity was 5% better at 321,000 seeds ha^{-1} compared to 222,000 seeds ha^{-1} in 2015 (Table 3). There was no significant main effect in 2016 for seedling emergence rates or emergence uniformity (Table 3). However, the planting speed by seeding rate interaction affected both the 25% emergence rate and the emergence uniformity (Table 3). In 2016, soybean seedlings needed more time (more GDU$_{°C}$) to reach 25% emergence rate when planted at 20 kph at 222,000 seeds ha^{-1} compared to all other planting speeds and seeding rates (Table 4). The 20 kph at 222,000 seeds ha^{-1} treatment also had the largest variation at 25% emergence progress (Table 4). In 2016, the study was conducted on a conventional tilled field that likely contributed to a more uniform emergence progress. Seedling emergence was minimally influenced by the planting speed and seeding rate over the 2 years (2015 and 2016) when seedling emergence was monitored. The initial seedling emergence rate differences were only evident at the early part of the emergence window even with the concern that planting at high speed may displace more soil and reduce the amount of soil on top of the seed.

Planter performance is many times evaluated by the seed delivery using plant population comparison (Nielsen, 1995), or by the uniformity of seed placement such as using SD or CV of the plant population (Nielsen, 1995; Staggenborg et al., 2004) or plant spacing (Virk et al., 2020) similarly to plant-to-plant uniformity research (Boomsma & Vyn, 2009; Daynard & Muldoon, 1983; Kovács & Vyn, 2014; Nielsen, 1991). Early plant stand, harvest plant stand, and associated CVs did not differ due to planting speed in 2015 and 2016 (Table 5). In 2016, the 12 kph planting speed resulted in a more uniform (lower CV) harvest plant stand ($p = 0.07$; Table 5) compared to the other two planting speeds. Pooled over the seeding rates in 2017, approximately 10,000 more plants ha^{-1} were counted for the 16 kph treatment at the early season and at harvest stand counts compared to the two slower planting speeds (Table 5); we do not have any explanation for why we observed plant population differences in 2017. As expected, increased seeding rates resulted in more plants at early and at harvest stand counts each year (Table 5). There was a planting speed by seeding rate interaction for the harvest stand CV in 2015 (Table 5). In 2015, the variability of harvest stands increased with decreasing planting speed for the 222,000 seeds ha^{-1} seeding rate, whereas higher plant stand variability was measured as the planting speed increased with the 321,000 seeds ha^{-1} seeding rate (Table 4).

More plants were counted as seeding rate increased (Table 5), and thus, shorter distance was measured between the plants as seeding rate increased (Mean PAS, Table 6). Planting speed only impacted the CV of PAS in 2016, when CV increased by 6% as the planting speed increased from 8 to 20 kph (Table 6). Higher seeding rates also increased PAS CVs by approximately 4% in 2015 and 2016, but not in 2017 (Table 6). Faster planting speed or higher seeding rate increases the metering unit speed (Table S2). Virk et al. (2020) documented increased variation in plant spacing and decreased yield with faster than 35 rotation min^{-1} (rpm) speed for the traditional John Deere metering unit and the Precision Planting eSet metering unit and seed plates. Virk et al. (2020) also reported 21%–36% CV in plant spacing in corn when the meter speed ranged from 15.4 to 43.0 rpm. In the current study planting soybean at higher seeding rates and higher speeds, the metering unit's speed ranged from 19.7 to 167.7 rpm (Table S2), whereas CV of PAS ranged between 30% and 42% (Figure 2). The faster planting speed and faster metering unit

TABLE 4 Effects of planting speed × seeding rate interaction on 90% emergence progress and harvest stand coefficient of variation (CV) in 2015, and air heat unit accumulation from planting to reach 25% emergence and its CV in 2016 using the John Deere ExactEmerge 1775NT planter near West Lafayette, IN, USA.

		2015		2016	
		90% emergence	Harvest plant stand	25% emergence	
Planting speed (kph)	Seeding rate (seeds ha^{-1})	CV (%)	CV (%)	Mean (GDU$_{°C}$)	CV (%)
8	222,000	11.3 bc	14.2 a	72.8 b	1.1 b
	321,000	14.3 abc	6.5 c	72.6 b	1.6 b
	420,000	–	–	72.3 b	0.4 b
12	222,000	18.8 ab	8.6 bc	72.2 b	0.6 b
	321,000	13.8 bc	6.3 c	73.1 b	1.5 b
	420,000	–	–	72.3 b	0.4 b
16	222,000	22.1 a	9.5 bc	72.5 b	0.0 b
	321,000	7.9 c	11.2 ab	72.9 b	2.0 b
	420,000	–	–	72.4 b	0.3 b
20	222,000	–	–	75.2 a	7.2 a
	321,000	–	–	72.2 b	0.5 b
	420,000	–	–	72.2 b	0.6 b

Note: Different lower case letters indicate statistical differences between treatments within a column at $p = 0.05$.

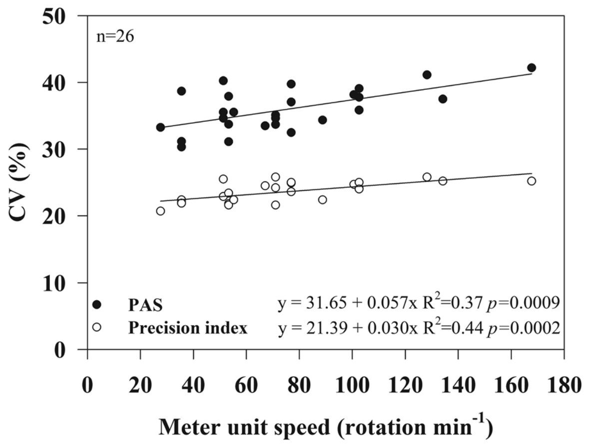

FIGURE 2 Relationship between plant available spacing (PAS), precision index, and planter meter unit speed using the John Deere ExactEmerge 1775NT planter at different planting speeds and seeding rates. Respective regression equations, coefficient of determinations (R^2), and model statistical significances are presented next to the legend.

speed also increased the PAS CV in Virk et al. (2020) publication. The highest metering speed in our study was four times faster than in Virk et al. (2020) due to higher seeding rates (Table S2), whereas the CV were only 6% higher compared to the aforementioned study. Mean soybean PAS is generally lower (3–8 cm) compared to corn PAS (15–17 cm) for the typical seeding rates of the respective crops; thus, smaller variations in plant spacing will yield larger CVs. There are limited publications that evaluated planter performance in soybean and none measured CV of plant spacing.

Distributions of PAS are presented in Figures 3–5 for 2015–2017, respectively, and the associated quality parameters are presented in Table 6. The multiple index (D) increased from 1.7% to 3.7% in 2016 as planting speed increased (Table 6; Figure 4). Similar increasing trend was observed in 2015 (p = 0.08) while planting speed did not affect D in 2017 (Table 6 and Figures 3 and 5). Higher seeding rates increased the D two-to-threefold across planting speeds in each growing season (Table 6; Figures 3–5).

The miss index (M) decreased from 21.6% to 17.6% in 2017 as planting speed increased (Table 6; Figure 5), whereas M was not affected by planting speed in the first 2 years of the experiment. The M increased approximately 3%–5% as seeding rates increased in 2015 and 2017 (Table 6; Figures 3 and 5).

The quality of feed index (A) quantifies the accurately placed seeds or plants. Higher values of this index indicate better performance. The A decreased from 78% to 67.5% in 2016 but increased from 77% to 81% in 2017 as planting speed increased (Table 6 and Figures 4 and 5). Decreasing trend of A was also measured in 2015 with increasing planting speeds (p = 0.06, Table 6; Figure 3). The A decreased by approximately 5%–7% as seeding rate increased from 222,000 to 321,000 seeds ha^{-1} in 2015 and 2017 (Table 6; Figures 3–5).

Comparison of the multiple and miss indices provided indications on the planter performance. The D is a true representation of close seed placement by the planter; however, it is impossible to separate if the close seed placement was due to

TABLE 5 Planting speed and seeding rates effect on early season and harvest stand and their coefficient of variation (CV), grain yield, and grain moisture content from 2015 to 2017 using the John Deere ExactEmerge 1775NT planter in Indiana.

		Early plant stand		Harvest plant stand			
Planting speed (kph)	**Seeding rate (seeds ha^{-1})**	**Mean (plants ha^{-1})**	**CV (%)**	**Mean (plants ha^{-1})**	**CV (%)**	**Grain yield (Mg ha^{-1})**	**Grain moisture (%)**
2015							
8		239,300	7.6	226,500	10.3	4.4	12.7 ab
12		247,500	6.1	235,500	7.4	4.6	12.9 a
16		242,500	7.7	228,700	10.4	4.4	12.5 b
	222,000	200,000 B	8.3	190,800 B	10.8 A	4.5	12.7
	321,000	286,200 A	6.0	269,700 A	8.0 B	4.5	12.7
$p < F$	Planting speed	0.31	0.50	0.25	0.07	0.18	0.050
	Seeding rate	<0.0001	0.06	<0.0001	0.021	0.99	0.85
	Planting speed × seeding rate	0.84	0.97	0.79	0.009	0.15	0.09
2016							
8		235,300	18.0	176,600	23.2	5.0	13.1
12		242,600	15.0	189,100	17.2	5.0	13.1
16		230,500	13.7	179,600	16.1	5.0	13.0
20		220,600	19.2	166,200	25.1	4.9	13.0
	222,000	151,900 C	22.6	134,500 C	23.0	4.9	13.0
	321,000	240,300 B	13.1	187,400 B	19.0	5.0	13.1
	420,000	320,000 A	13.7	216,500 A	19.1	5.0	13.1
$p < F$	Planting speed	0.35	0.53	0.67	0.14	0.73	0.83
	Seeding rate	<0.0001	0.056	<0.0001	0.49	0.29	0.77
	Planting speed × seeding rate	0.58	0.82	0.73	0.79	0.42	0.99
2017							
8		214,500 b	10.7	199,800 b	11.1	3.8 b	9.2
12		216,300 b	9.4	206,000 b	9.2	4.1 a	9.2
16		226,300 a	5.7	216,600 a	6.4	3.8 b	9.7
	222,000	182,700 B	8.1	176,600 B	8.0	3.9	9.4
	321,000	258,600 A	9.2	240,800 A	9.8	3.9	9.3
$p < F$	Planting speed	0.046	0.13	0.009	0.23	0.01	0.66
	Seeding rate	<0.0001	0.58	<0.0001	0.41	0.62	0.92
	Planting speed × seeding rate	0.32	0.36	0.10	0.57	0.67	0.48

Note: Different lowercase letters indicate statistical differences between different planting speeds within a growing season and within parameter column at $p = 0.05$. Different uppercase letters indicate statistical differences between different seeding rates within a growing season and within parameter column at $p = 0.05$.

singulation/seed metering error, seed delivery, or potentially seed movement in the seed furrow after the seed release from the brush belt (e.g., seed is bouncing within the seed-furrow). The M value can be misleading due to the methodology of the measurements. The various plant uniformity index calculations were based on the distance between emerged plants at early season. Overestimation of the miss index can come from three sources: (i) planter performance (the planter did not drop a seed), (ii) not emerging seedling (emergence failure), or (iii) plant died after emergence but before plant spacing measurement. The estimated final emergence (i.e., live plants relative to the target seeding rate) was 90% in 2015, 68%–74% in 2016, and 82% in 2017 relative to the target seeding rate. Some portion of the M was likely due to failed seedling emergence, rather than the planter's seed delivery failure, especially in 2016 and 2017 when weather conditions were cool and wet

TABLE 6 Planting speed and seeding rates effect on plant uniformity parameters: plant available spacing (PAS), multiple index (D), miss index (M), quality of feed index (A), and precision index (C) from 2015 to 2017 using the John Deere ExactEmerge 1775NT planter in Indiana

Planting speed (kph)	Seeding rate (seeds ha^{-1})	PAS (cm)	PAS CV (%)	*D* (%)	*M* (%)	*A* (%)	*C* (%)
2015							
8		5.64	32.9	4.06	8.14	87.80	22.48 b
12		5.52	34.1	5.32	7.69	86.99	22.70 b
16		5.79	36.4	5.94	11.00	83.07	24.94 a
	222,000	6.66 A	32.0 B	3.28 B	7.39 B	89.33 A	23.54
	321,000	4.64 B	36.9 A	6.93 A	10.50 A	82.57 B	23.20
$p < F$	Planting speed	0.14	0.13	0.08	0.18	0.06	0.005
	Seeding rate	<0.0001	0.0001	<0.0001	0.037	0.0005	0.57
	Planting speed × seeding rate	0.12	0.69	0.60	0.94	0.96	0.066
2016							
8		5.19	33.1 c	1.70 c	20.19	78.10 a	23.27
12		5.20	34.8 bc	3.31 bc	22.00	74.68 ab	24.34
16		5.27	36.6 ab	3.71 b	24.74	71.55 bc	24.77
20		5.29	39.2 a	6.00 a	26.53	67.46 c	24.46
	222,000	7.1 A	33.3 B	1.75 C	23.40	74.85	23.09
	321,000	4.9 B	36.7 A	3.79 B	21.73	74.49	24.64
	420,000	3.7 C	37.8 A	5.52 A	24.98	69.50	24.90
$p < F$	Planting speed	0.91	0.03	0.0005	0.17	0.009	0.15
	Seeding rate	<0.0001	0.02	0.0002	0.45	0.07	0.07
	Planting speed × seeding rate	0.65	0.13	0.17	0.26	0.17	0.64
2017							
8		6.16 a	39.5	1.08	21.65 a	77.27 b	23.69
12		6.12 a	38.8	1.82	21.57 a	76.61 b	23.33
16		5.85 b	35.5	1.42	17.59 b	80.99 a	22.81
	222,000	7.07 A	37.2	0.64 B	17.92 B	81.44 A	21.70 B
	321,000	5.02 B	38.6	2.24 A	22.62 A	75.14 B	24.86 A
$p < F$	Planting speed	0.03	0.15	0.56	0.046	0.03	0.41
	Seeding rate	<0.0001	0.43	0.01	0.004	0.0002	<0.0001
	Planting speed × seeding rate	0.59	0.96	0.32	0.21	0.40	0.61

Note: Different lowercase letters indicate statistical differences between different planting speeds within a growing season and within parameter column at $p = 0.05$. Different uppercase letters indicate statistical differences between different seeding rates within a growing season and within parameter column at $p = 0.05$.

immediately following the planting. However, we only evaluated the planter performance based on the emerged plants and not the seed delivered. In previous publications, the M increased from 2% to 8% for corn as planting speed increased 6–14 kph, and in 1 site-year from 8% to 14% between 9 and 14 kph speed ranges using a MaxEmerge planter with standard metering units (Staggenborg et al., 2004). The reported D were similar or higher than observations in current study that used higher planting speeds and higher seeding rates (Table 6; Figures 3–5). Bortoli et al. (2021) reported D increase from 5% to up to 30% as planting speed increased from 3 to 9 kph in soybean, which is higher than the observation in this study. Staggenborg et al. (2004) documented M between 8% and 18%. The M in the current study in 2015 was at the lower range (8%–11%) relative to the Staggenborg et al. (2004) study, but M in 2016 and 2017 was higher (Table 6) likely due to poorer emergence during cool and wet conditions that decreased plant population in both years, therefore increasing the proportion of M. The increasing D and M also impacted the A (Table 6). Generally, A decreased with increasing speed; however, in 2017, the increased A at higher speed was due to the better emergence and higher plant population (Table 5)

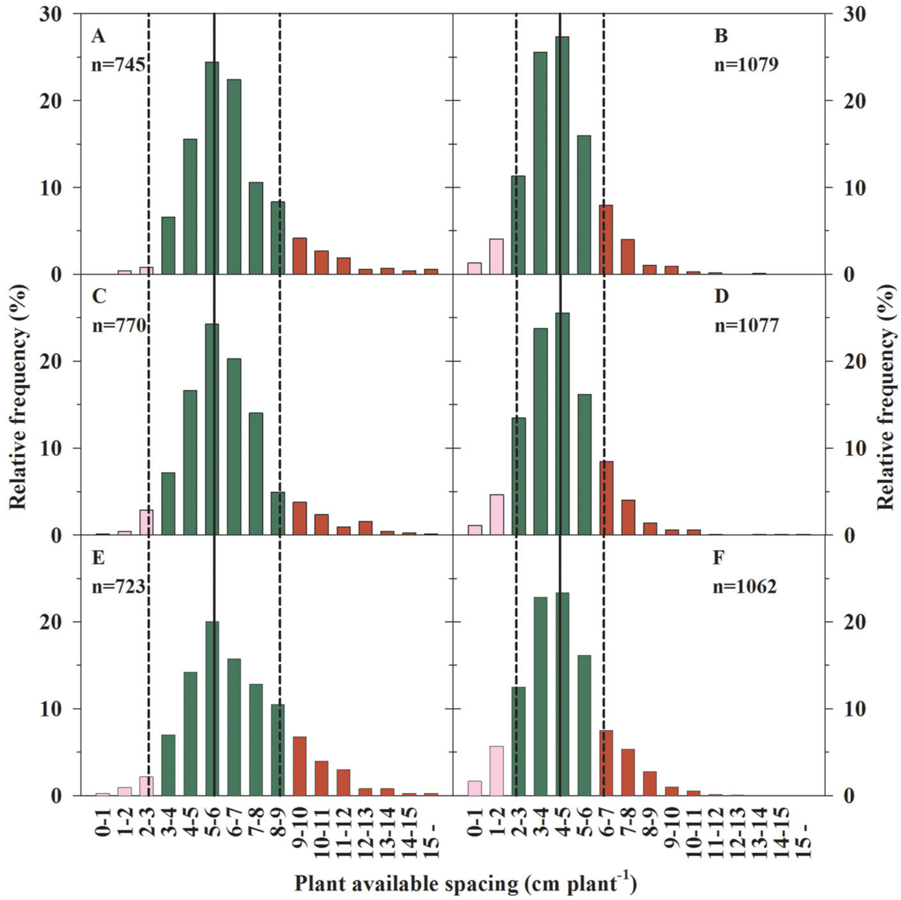

FIGURE 3 Distribution of plant available spacing (PAS) at 8 kph (A and B; 5 mph), 12 kph (C and D; 7.5 mph), and 16 kph (E and F; 10 mph) planting speeds and with 222,000 seeds ha^{-1} (A, C, and E; 90,000 seeds ac^{-1}) and 321,000 seeds ha^{-1} (B, D, and F; 130,000 seeds ac^{-1}) seeding rate treatments with John Deere NT1775 high-speed planter in 2015 near West Lafayette, IN, USA. Number of observations included in each panel. The solid line represents the reference PAS (PAS_{ref}) for the target seeding rates, and the dotted lines represent the half and one and a half times PAS_{ref}.

in the 16 kph treatment, resulting in more plants within the desired PAS range improving planter performance (Table 6).

Kachman and Smith (1995) described the C as a measure of the variability in plant spacing after accounting for (i.e., eliminating) variability due to both multiples and skips; mathematically, this is the CV of plant spacing within the accurately delivered seeds or plants. A lower C index value would mean a narrower and more peaked distribution of PAS around PAS_{ref} and signaling an overall better, on-target seed delivery. Precision index increased from 22.5% to nearly 25% when planting speed increased from 8 to 16 kph in 2015 and increased from 21.7% to nearly 24.9% when seeding rate increased from 222,000 to 321,000 seeds ha^{-1} in 2017 (Table 6; Figures 3–5). Kachman and Smith (1995) discussed a practical upper limit of 29% for precision, which would describe a plant spacing that is uniformly distributed within the target zone (between the 0.5 and 1.5 PAS of the target plant spacing). The wider PAS distribution spread (flattening of distribution) with increased planting speed in 2015 is also depicted in Figure 3, as the relative frequency of the peak PAS decreased with increasing planting speed (downward on the graph), and PAS distribution was flatter within the dashed lines. Similar response was observed for the increasing seeding rate in 2017 (Figure 5). We consider the uniformity of the plant spacing within the accurately placed seeds ($0.5 \times PAS \leq PAS_{ref} \leq 1.5 \times PAS$), excluding the multiples and skips; the CVs of plant spacing were approximately 10% lower than when the CVs for all the emerged plants (Figure 2). In addition, the CV only increased by 0.03% for each rotation min^{-1} meter unit speed increase compared to the 0.05% increase for PAS (Figure 2).

Grain yield was neither impacted by planting speed nor by seeding rate in the first 2 years of the study (Table 5). However, in 2017, grain yield was approximately 0.25 Mg ha^{-1} higher with the 12 kph planting speed compared to the 8 or 16 kph speeds (Table 5). Grain moisture content was not different due to planting speed or seeding rate, except in 2015 due to planting speed (Table 5). Grain moisture was 0.4% higher with the 12 kph planting speed relative to the 16 kph, whereas the other planting speed combinations were not statistically different from each other. This 0.4% moisture difference likely will not impact harvest scheduling or harvest results.

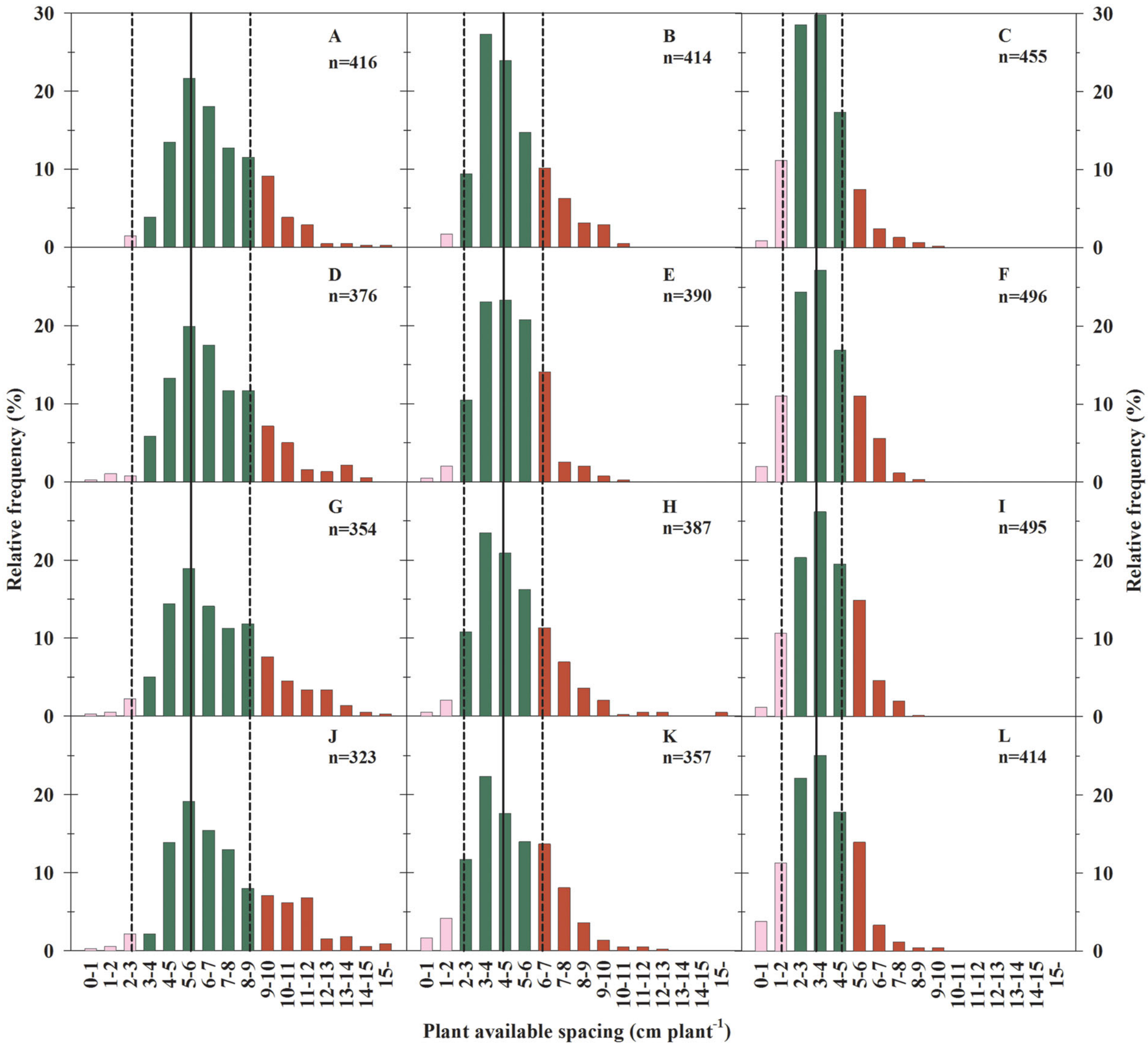

FIGURE 4 Distribution of plant available spacing (PAS) at 8 kph (A–C; 5 mph), 12 kph (D–F; 7.5 mph), 16 kph (G–I; 10 mph), and 20 kph (J–L; 12.5 mph) planting speeds and with 222,000 seeds ha^{-1} (A, D, G, and J; 90,000 seeds ac^{-1}), 321,000 seeds ha^{-1} (B, E, H, and K; 130,000 seeds ac^{-1}), and 420,000 seeds ha^{-1} (C, F, and L; 170,000 seeds ac^{-1}) seeding rate treatments with the John Deere NT1775 high-speed planter in 2016 near Lafayette, IN, USA. Number of observations included in each panel. The solid line represents the reference PAS (PAS_{ref}) for the target seeding rates, and the dotted lines represent the half and one and a half times PAS_{ref}.

Masino et al. (2018) documented that soybeans are less sensitive to spatial nonuniformity compared to temporal nonuniformity [i.e., later emerged soybean (seedling emerging when neighboring soybeans are at the V1 growth stage)]. Masino et al. (2018) documented yield decline with nonuniform spatial distribution with a variety that had a low branching ability. O'Brien and Hatfield (2021) also documented that biomass production and grain yield were not impacted by increased plant-to-plant variability. Similar to the previous research, grain yield was not influenced by the different spatial distributions in this study. However, others have documented decreased grain yield with nonuniform plant spatial distribution (Bortoli et al., 2021; Xu et al., 2021).

Soybean can adapt to different seeding rates or plant populations to produce similar grain yields based on adjustments in branching, pod distribution, and seed size. De Bruin and Pedersen (2009) reported grain yield response plateaued between 200,000 and 230,000 plants ha^{-1}. Similar were concluded from on-farm trials conducted in Indiana (Kovács & Casteel, unpublished data) that grain yield response was limited above 200,000 harvest plants ha^{-1} across most of the regions in Indiana. Further, other publications documented 150,000–200,000 plants ha^{-1} differences in (optimal) final plant stand in order to reach 95% of the maximum yield (De Bruin & Pedersen, 2008a, 2008b). Final plant stand in this study was near to or above 200,000 plants ha^{-1} in 2015 and 2017, but it

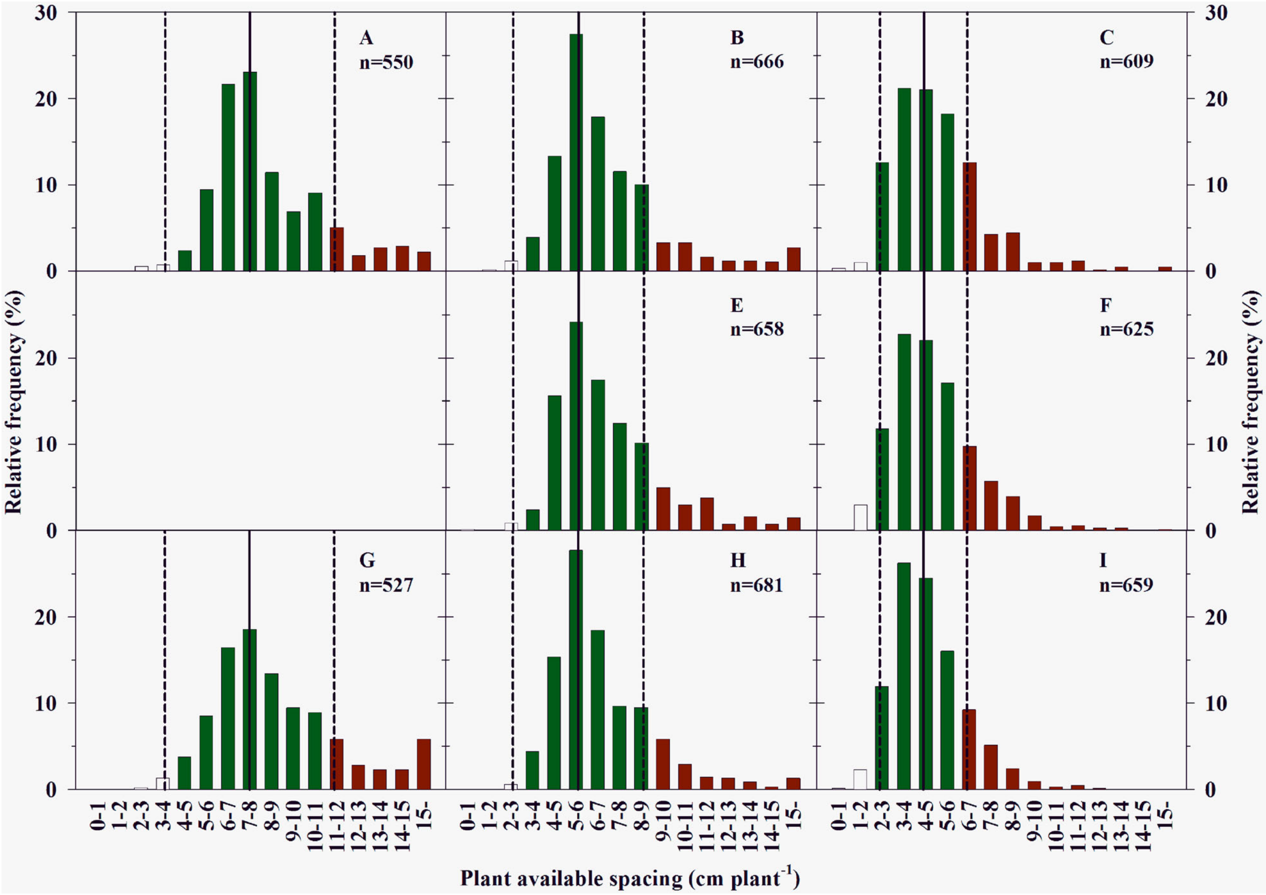

FIGURE 5 Distribution of plant available spacing (PAS) at 8 kph (A–C; 5 mph), 12 kph (E and F; 7.5 mph), and 16 kph (G–I; 10 mph) planting speeds and with 173,000 seeds ha^{-1} (A and G; 70,000 seeds ac^{-1}), 222,000 seeds ha^{-1} (B, E, and H; 90,000 seeds ac^{-1}), and 321,000 seeds ha^{-1} (C, F, and I; 130,000 seeds ac^{-1}) seeding rate treatments with the John Deere NT1775 high-speed planter in 2017 near Lacrosse, IN, USA. Number of observations included in each panel. The solid line represents the reference PAS (PAS_{ref}) for the target seeding rates, and the dotted lines represent the half and one and a half times PAS_{ref}.

TABLE 7 Planting speed effect on early and harvest plant stand and its uniformity, on grain yield and grain moisture content at 173,000 seeds ha^{-1} seeding rate in 2017 using the John Deere ExactEmerge 1775NT planter in Indiana.

	Early plant stand		Harvest plant stand		Grain yield	
Planting speed	Mean (plants ha^{-1})	CV (%)	mean (plants ha^{-1})	CV (%)	(Mg ha^{-1})	Grain moisture (%)
8 kph	150,200	5.8	148,800 a	8.8	3.8	9.1
16 kph	143,900	9.3	137,600 b	12.5	3.9	9.0
$p < F$	0.17	0.25	0.03	0.22	0.86	0.40

Note: Pairwise contrast significance for each parameter presented at the bottom of the table. Different lower case letters indicate statistical differences between treatments within a column at $p = 0.05$.

was around 25,000 plants ha^{-1} lower in 2016 (Table 5), which places this study within the range and agreeing of the previous research. Planting speed did not impact plant stand at harvest in 2015 and 2016, but the 16 kph planting speed treatments in 2017 had approximately 10,000 plants ha^{-1} more than the 8 and 12 kph planting speeds. Moore (1991) documented yield increase (257 kg ha^{-1}) in one of the 2 years with equidistance soybean placement compared to non-equidistance plant spacing. In this study, the more uniform plant spacing (lower PAS CV) did not increase soybean yields.

The pairwise comparison between the 8 and 16 kph planting speeds for the low seeding rate only (173,000 seeds ha^{-1}) did not indicate significant differences (p-values ranged between 0.06 and 0.86) in planter performance, except the approximately 10,000 plants ha^{-1} higher harvest plant stand for the 8 kph speed (Tables 7 and 8).

TABLE 8 Planting speed effect on plant available spacing (PAS) and its uniformity, and on plant uniformity parameters: multiple index (D), miss index (M), quality of feed index (A), and on precision index (C) at 173,000 seeds ha^{-1} seeding rate in 2017 using the John Deere ExactEmerge 1775NT planter in Indiana.

	PAS					
Planting speed	Mean (plants ha^{-1})	CV (%)	D (%)	M (%)	A (%)	C (%)
8 kph	8.6	31.0	0.9	84.5	14.6	20.7
16 kph	9.1	34.9	0.8	80.0	19.2	22.4
$p < F$	0.06	0.12	0.77	0.07	0.06	0.11

Note: Pairwise contrast significance for each parameter presented at the bottom of the table.

4 | CONCLUSION

We evaluated the Exact Emerge planter over three growing seasons in soybean production at various planting speeds and seeding rates. Generally, planting speed did not influence seedling emergence (timing, rate, and uniformity) when seedling emergence was monitored. Plant population was largely not affected by planting speed. Seeding accuracy decreased up to 7% (measured as the quality of feed index on emerged plants) when planting speed increased from 8 to 16 kph in the first 2 years, and by about 10% when planting speed increased from 8 to 20 kph in 2016. However, seeding accuracy increased by 3% when planting speed increased from 8 to 16 kph in 2017. Planting speed did not affect grain yield in two of the three seasons, and a 0.25 Mg ha^{-1} higher yield was achieved with 12 kph planting speed in 2017.

With increased planting speed, one needs more attention to setting the planter prior to operation, especially adjusting row cleaners if used. Increasing planting speed can be achieved without detrimentally affecting plant population, plant spacing, and yield in soybean.

AUTHOR CONTRIBUTIONS

Péter Kovács: Conceptualization; data curation; formal analysis; investigation; methodology; supervision; visualization; writing—original draft. **Shaun N. Casteel**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interests.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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