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Optimization of Within-Row Plant Spacing Increases Nutritional Status and Corn Yield: A Comparative Study

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ABSTRACT

Uniform within-row plant spacing is a key crop management strategy to achieve high corn (*Zea mays* L.) yield. A new precision planting concept is emerging based on the use of modern devices in planters. The objective of this study was to investigate the impact of optimizing within-row plant spacing to enhance plant nutritional status and corn yield. The treatments investigated were (a) traditional planter with mechanical horizontal plate metering system (TP), (b) precision planter with vSet (Precision Planting, Tremont, IL) vacuum meter system (PP) and (c) PP pulled by a tractor equipped with an real time kinematic (RTK)-based auto-steering system (APP). The experimental design was a randomized block with three replications, and the plant evaluations were determined based on a main plot and a plant-to-plant study. Two types of vegetation indexes (VI and normalized difference, NDVI) were used for assessing plant nutritional status. A high standard of uniform plant spacing (CV < 10%) was required to achieve the highest corn yield. Optimizing the within-row plant spacing resulted in higher VI and NDVI. Based on the average of two experiments, PP improved the uniformity of plant spacing (CV = 22.5%) compared to TP (CV = 38.7%). This optimization of within-row plant spacing increased the corn yield by 10.7%. Only in the year with higher corn yield potential did APP result in a yield increase of 6.9% in relation to PP. Although the precision planters investigated had decreased the error in plant distribution, no one reached the plant spacing uniformity required to achieve higher corn yields.

Core Ideas

- For every 10 percentage points increase in CV, yield decreased 1.22 Mg ha^{-1}.
- A higher plant spacing uniformity is necessary to achieve high yields.
- Different planter types produced distinct within-row plant spacing uniformity.

A new concept of precision planting is emerging in precision agriculture based on the use of modern devices in planters and tractors (Shearer and Pitla, 2013). Non-uniform within-row plant spacing and inadequate plant population are key factors that decrease corn yield (Maddonni and Otegui, 2004; Sangoi et al.; 2010; Chim et al., 2014). This yield decrease is due to corn sensitivity to intraspecific competition; corn does not tolerate the close proximity of plants within a row and has limited ability to produce fertile tillers, usually producing one ear per plant even when widely spaced (Sangoi et al., 2011).

Vieira et al. (2006), who performed a study in Brazil, found that corn yield was negatively affected by non-uniform within-row plant spacing and reported that the critical CV for plant spacing was <20%. Andrade and Abbate (2005) reported that an increase in the CV of within-row plant spacing in Argentina reduced individual corn plant yield by 0.219 g for each 1% increase in CV. In a study performed in the United States, Nielsen (2001) reported that approximately 156 kg ha^{-1} of grain yield was lost for each 2.5 cm increase in SD of plant spacing in a row. In the same way, Doerge et al. (2002) reported a yield decrease of 110 kg ha^{-1} for every 1 cm increase in SD of plant spacing. Carlson et al. (2003) reported that every 1 cm increase in SD resulted in a corn yield loss of 100 kg ha^{-1}.

Non-uniform within-row plant spacing may be due to the use of planters with a mechanical system consisting of horizontal plates, operating at excessive speeds (Liu et al., 2004), low performance under soil compaction condition, non-sensibility to texture and moisture variability across a field, among other factors (Martin et al., 2005). Even planters equipped with pneumatic seed meters are susceptible to several distribution and control errors, which compromise their capacity to effectively provide uniform seed distribution. In addition, these planter types are usually operated at high speed, without observing the optimal conditions of soil moisture and the spatial variability of soil

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Abbreviations: ALS, active light source; APP, auto-steering precision planting; DGPS, differential global positioning system; ECa, apparent electrical conductivity NDVI, normalized difference vegetation index; PP, precision planting; R_{760}, wavelength range of 760 nm; R_{730}, wavelength range of 730 nm; RTK, real time kinematic; TP, traditional planting; VI, vegetation index; r_{NIR}, fraction of emitted near infrared radiation; r_{Red}, fraction of emitted red radiation.

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resistance, contributing to the non-uniform within-row plant arrangement observed in some cases (Staggenborg et al., 2004).

An evaluation of 48 fields in southern Brazil revealed high variability in within-row plant spacing, although most fields were successful in terms of obtaining the target plant population. In 92% of the fields investigated, the plant spacing CV was higher than 20% (Schimandeiro et al., 2006). Non-uniform within-row plant spacing was also previously reported in a study investigating 350 fields in Indiana and Ohio, where only 16% of the plant spacing was classified as satisfactory with SD lower than 7 cm. In addition, in 60% of the fields investigated, the SD ranged between 10 and 12 cm and in another 24%, the SD was higher than 15 cm (Nielsen, 2001). In 46 transects of fields in Argentina, Mexico and United States, non-uniform within-row plant spacing contributed to high variability of corn yield in a plant-to-plant study (Martin et al., 2005). In this case, the corn yield variability was 2.76 Mg ha^{-1} and was attributed to: (i) non-uniform within-row plant spacing, (ii) irregular seeding depth caused by spatial variability in soil moisture, texture and compaction, and (iii) uneven emergence.

Specific measures such as the multiple index, miss index, quality of feed index, and precision (ISO, 1984) can be used to establish standard distance ranges (qualitative values), omitting fine-tuning optimization, and can be well assessed using SD and CV parameters (quantitative values).

The uniform within-row plant spacing is an essential method to improve crop yield. The objective of this study was to establish the relationship between within-row plant spacing, the nutritional plant status assessed by crop sensor technologies and corn yield using distinct types of planters and devices for precision planting.

MATERIALS AND METHODS

Site Descriptions

This study was conducted at two sites in Carazinho, Rio Grande do Sul, Brazil, during the agricultural years of 2012/2013 (Exp. I) and 2013/2014 (Exp. II). The two rainfed fields were 500 m apart and had been managed under precision agriculture (PA) as part of the Aquarius Project (www.ufsm.br/projetoaquarius). The first site is located at geographical coordinates 28.32′ S and 52.47′ W, while the second site is located at coordinates 28.32′ S and 52.72′ W, both with an average altitude of 570 m. The climate in this region is classified as wet subtropical (Cfa), according to Köppen (1938); the average temperature of the warmest month is January (24.6°C) and the coldest month is June (12.9°C), with annual rainfall ranging between 1500 and 1750 mm. The soil is classified as a Typic Hapludox (Soil Survey Staff; 2010) with loamy to clayey texture (Embrapa-Centro Nacional de Pesquisa de Solos, 2006). The two experimental sites consisted of annual crops that have been managed under long-term no-till (>20 yr). The main cash crops during the summer are soybean [*Glycine max* (L.) Merr.] and corn in a rotation system with predominance of the former. In winter, wheat (*Triticum aestivum* L.) is the main cash crop, rotated with black oat (*Avena strigosa* L.), which is used as a single cover crop or mixed with radish oil (*Raphanus sativus* L.).

Experimental Procedures

The study was performed based on an experimental design of randomized blocks with three replications and the following treatments: (a) traditional planter with mechanical horizontal plate metering system (Model Victória, Stara SA, Não-Me-Toque, Rio Grande do Sul, Brazil), pulled by a tractor without GPS-enabled navigation technology-traditional planter (TP); (b) planter with vSet (Precision Planting, Tremont, IL) vacuum meter system (Model Victória Top DPS, Stara SA, Não-Me-Toque, Rio Grande do Sul, Brazil) pulled by a tractor without GPS-enabled navigation technology (PP); and (c) PP pulled by a tractor equipped with an auto-guiding system (Model Topcon System 150, Topcon Corporation, Tokyo, Japan) with an RTK-based auto-steering system (APP). The planters produced 10 rows with a 0.50-m row spacing; this row space is used by most corn growers in Brazil. A single macroplot and an associated microplot were established as follows: (i) The macroplots were 11 by 600 m in length for Exp. I and 11 by 90 m for Exp. II, corresponding to total areas of 6600 m^2 and 990 m^2, respectively; (ii) The microplots were 1.5 m (three corn rows) by 2.7 m in length, corresponding to an area of 4.05 m^2, which was located in a central position within the macroplot. In the microplots, individual plants were banded and numbered to study plant-to-plant spacing, crop sensing, and record the yield. The localization of the microplots in advanced corn stages was performed using a DGPS OmniSTAR corrected signal. In addition, transects of five plants in the macroplots were selected to obtain a large range of within-row plant spacing, corn nutritional status, and grain yield (Fig. 1).

Soil chemical analysis (0–10 cm) was determined according to the standard methods described in Tedesco et al. (1995). The average apparent electrical conductivity (ECa) values as determined by Veris 3100 (Veris Technologies Inc., Salina, KS) at a depth of 0 to 30 cm are shown in Table 1. Fertilization was adjusted to a corn yield goal of 10 Mg ha^{-1} according to regional fertilizer recommendation (CQFS-RS/SC, 2004). At planting, 61.2 kg ha^{-1} of P and 27 kg ha^{-1} of N were applied in the row and 48.1 kg ha^{-1} of K was broadcast. In the four- and eight-leaf collar stages (V4 and V8, respectively; Ritchie et al., 1993), broadcast N was split into two equal applications of 80 kg ha^{-1} of N. The nutrient sources were urea (44% N), ammonium diphosphate-DAP (18% N and 20.4% P) and potassium chloride (48.1% K_2O).

The genetic material used in both experiments was Pioneer 30F53YH, which is commonly planted in southern Brazil. The corn was seeded on 15 Oct. 2013, and on 11 Sept. 2014, for Exp. I and II, respectively, with a target plant population of 75,000 ha^{-1}. The seeding depth was adjusted to 5 cm, with a speed of 5 km h^{-1}. Seed vigor and germination in both experiments were 91 and 95%, respectively.

Measurements

Within-row plant spacing uniformity was assessed using the CV and SD of plant spacing evaluated at the V4 growth stage. These indexes were determined in both studies: the transect in the macroplot and in the plant-to-plant study in the microplots (Fig. 1).

In the macroplot, the VI was determined at the V8 growth stage using an optical crop sensor N-Sensor (Model ALS, Yara International ASA, Duelmen, Germany) attached to the top of the tractor cabin at approximately 3.8 m above the soil surface. The sensor scanned oblique ellipses of 3.0 m on both sides of the tractor, following the movement of the machine. In a previous study, VI values were well correlated with the amount of plant N uptake (Jasper et al., 2009; Portz et al., 2012; Bragagnolo et al., 2013; Amaral et al., 2014). The N-Sensor Model ALS (Yara

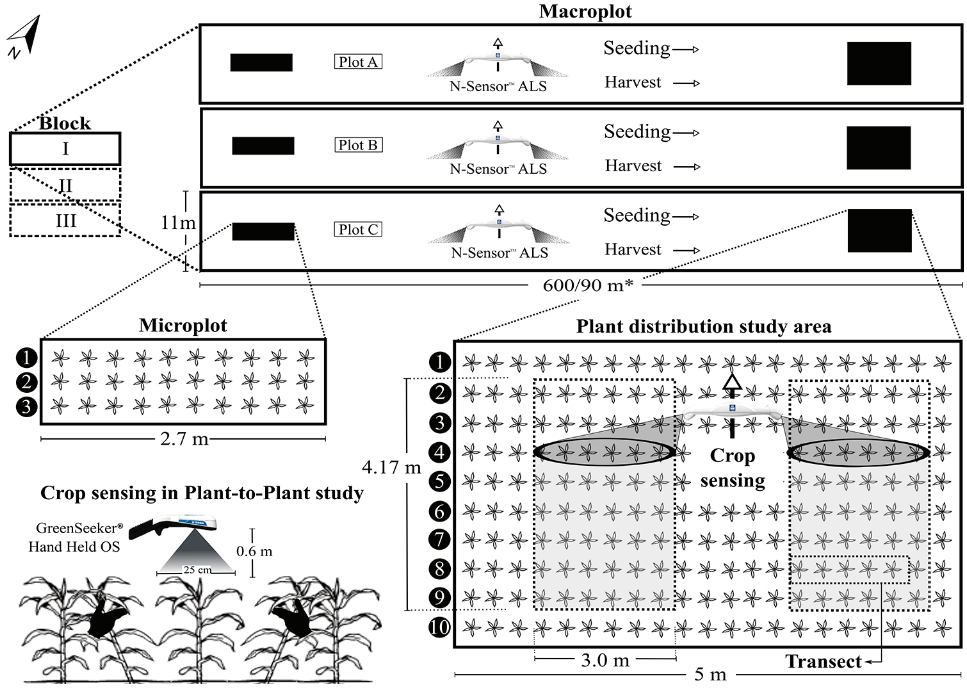

Fig. 1. Schematic experimental design used in the study. Trat A = TP, Trat B = PP, and Trat C = APP.

International SAS, Duelmen, Germany) was operated at a speed of 15 km h^{-1}, recording data every second, resulting in a total area scanned of 25 m^2 (eight corn rows with a width of 0.5 m). The VI was calculated according to Eq. [1]:

$$\mathrm{VI} = (\ln R_{760} - \ln R_{730}) \times 100 \qquad [1]$$

where R_{760} = wavelength range of 760 nm and R_{730} = wavelength range of 730 nm.

In the microplot at V7 growth stage, each plant identified in the plant-to-plant study was measured for normalized difference vegetation index (NDVI) using a single GreenSeeker (Trimble Navigation Limited, Sunnyvale, CA) (Model Hand Held Pocket Optical Sensor). The sensor field view is oval, and its size increases with the height of the sensor above the target; the ratio between height and width is 41.7% (Trimble, 2016). In the current study, the height of the GreenSeeker was fixed at 0.60 m above the canopy, and the foot-print was 0.2502 m (Fig. 1). In a previous study, NDVI was well correlated with the chlorophyll content and the plant N nutritional status (Martin et al., 2007). The NDVI was calculated according to Eq. [2]:

$$\mathrm{NDVI} = \frac{\rho\mathrm{NIR} - \rho\mathrm{RED}}{\rho\mathrm{NIR} + \rho\mathrm{RED}} \qquad [2]$$

where ρNIR = fraction of emitted NIR radiation returned from the sensed crop (reflectance) and ρRED = fraction of emitted red radiation returned from the sensed crop (reflectance).

Corn yields for the transects in the macroplots and in the plant-to-plant study in the microplots were assessed manually by collecting the ears of each plant and estimating the grain yield based on a final plant population of each row evaluated. In the macroplots, yield was evaluated with a combine (Model New Holland TC5090, New Holland AG, Curitiba, Paraná, Brazil) equipped with a mass flow sensor coupled to a harvest grain elevator and moisture sensor. The combine head width coincides with the width of the planters. A grain yield monitor (Model Topper 4500, Stara SA, Não-Me-Toque, Rio Grande do Sul, Brazil) was used to record the yield and moisture data. The data were tabulated and the main sources of harvest data errors such as positioning errors (repeated coordinates) and improbable yield values were eliminated as proposed by Blackmore et al. (2003), through filtering using SMS (Ag Leader, Ames, IA) Advanced 15.20, The yield was adjusted to 13% corn grain moisture.

Rainfall distribution during the growing season was distinctly different between the 2 yr despite similar total rainfall for both years (Fig. 2).

In the first experiment, there was a better distribution of rainfall throughout the growing season, while in the second experiment, a drought period occurred during the corn flowering stage. In this case, cumulative rainfall in the period between

Table 1. Soil physical and chemical characteristics at 0- to 15-cm depth.

Exp.†	ECa	C‡	P	K	Al	Ca	Mg	CEC	pH (H_2O)	Clay
	μs cm^{-2}	g kg^{-1}			mg kg^{-1}			cmol kg^{-1}	1:1	g kg^{-1}
I	9.0	20.30	15.9	0.45	0.0	900	384	10.0	5.7	580
II	9.8	19.14	17.9	0.56	0.0	740	300	9.2	5.5	650

† Exp = Experiment; ECa = electric conductivity; C = soil organic carbon; P = phosphorus extracted by Melich-I, K = potassium, CEC = cation exchange capacity.

‡ Organic carbon estimated using Nelson and Sommers (1996).

the week preceding flowering and the two subsequent weeks was 15 mm, and the demand for this period was estimated to be 150 mm (Durães et al., 2004).

Statistical Analysis

Data for each dependent variable were analyzed using ANOVA using PROC GLIMMIX in SAS (SAS Institute, 2016. The SAS System for Windows, Version 9.04 University Edition, SAS Institute, Inc., Cary, NC). When the treatment effect was significant ($p \leq 0.05$), least significant differences between treatment means were determined using the Tukey adjustment with a significance level of $p < 0.05$. Data normality was tested using the PROC UNIVARIATE procedure in SAS.

RESULTS AND DISCUSSION

Non-Uniform Within-Row Plant Spacing Impacts Plant Nutritional Status and Corn Yield Loss

In the transect study performed in the macroplots, we found a large range in CV values for the within-row plant spacing along the row (Table 2). Based on these data, the CV of plant spacing had a negative linear relationship with plant nutritional status assessed using the NDVI and grain yield (Fig. 3). With respect to the NDVI, there was a mean decrease of 0.02 for every 10-percentage point increase in the CV value (Fig. 3). Along the transects, the grain yield in the first experiment ranged from 7.94 to 15.48 Mg ha^{-1} when the plant spacing CV ranged from 58.3 to 5.5%, respectively, compared with 5.03 to 12.28 Mg ha^{-1} when the CV ranged from 59.1 to 7.1%, respectively, in the second experiment. Thus, in this study, for every 10-percentage point increase in the plant spacing CV, the yield decreased by 1.44 and 0.99 Mg ha^{-1} in the first and second experiment, respectively (Fig. 3). The effect of non-uniform within-row plant spacing in this study was higher than previous reports in other experiments (Nielsen, 2001; Staggenborg et al., 2004; Sangoi et al., 2012). This can be partly explained by differences in the sensitivity of the hybrids investigated to the spatial plant arrangement and the methodology used in each study. Generally, in previous studies, this type of relationship was determined in small plots with manual handling (without seeders and tractors) (Sangoi et al., 2012) or in overseeded plots where plants were thinned (Staggenborg et al., 2004); both methodologies introduce some bias.

Increases in corn yield in response to decreased error in plant spacing have been widely reported in the literature (Nielsen, 2004; Liu et al., 2004; Sangoi et al., 2012). However, based on these results, one would expect a decrease in grain yield of 0.04 to 0.06 Mg ha^{-1} for every 1 cm increase in SD and of 0.06 to 0.13 Mg ha^{-1} for every 10-percentage point increase in the CV of plant spacing. The results reported in this study indicate that the decrease in corn yield caused by the uneven plant spacing was even more intense, based on the linear relationship between CV and yield loss. Sarlangue et al. (2007) and Thompson (2013) emphasized that corn yield response to within-row plant spacing uniformity was dependent on the morphological plasticity of the hybrid. Shorter-season hybrids could have limited yield plasticity in relation to longer-season hybrids. Doerge et al. (2002) conducted a 2-yr on-farm study in the United States and reported that for every 1 cm decrease in SD, there was an increase of 110 kg ha^{-1} in corn yield. This value is close to the 2-yr average observed in the current study. The results shown in Fig. 3 indicate that a high standard of precision plant spacing (CV < 10%) is necessary to achieve high corn yield.

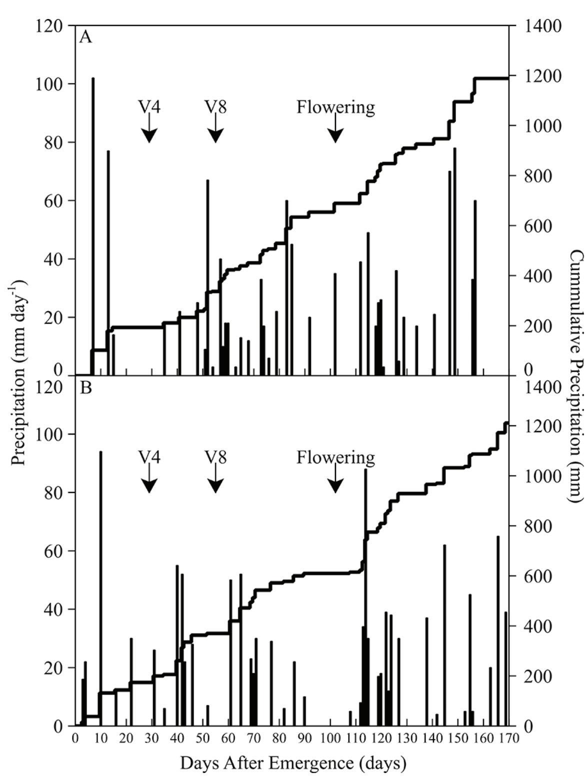

Fig. 2. Distribution of rainfall and accumulated rainfall during the crop cycle for (A) Exp. I and (B) II.

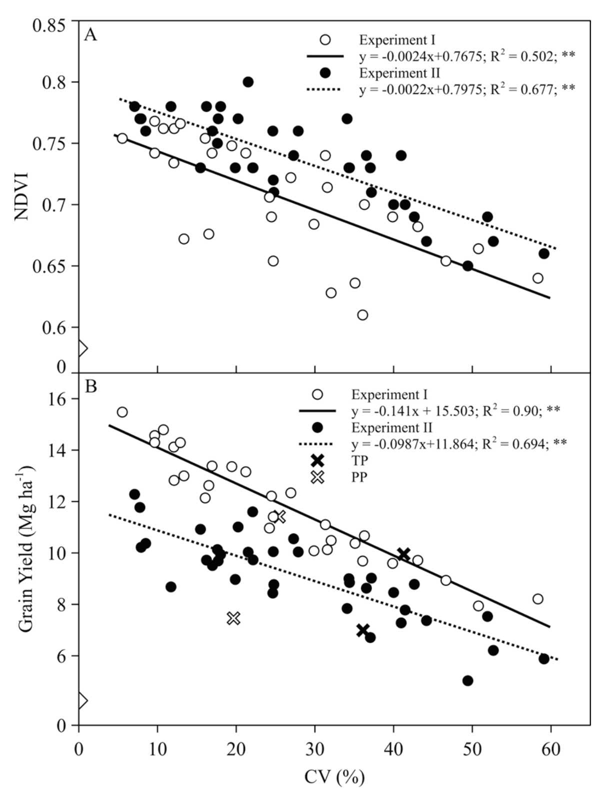

Fig. 3. Relationship of within-row plant spacing and (A) normalized difference vegetation index (NDVI) and (B) corn grain yield for Exp. I and II in the transect (plant-to-plant study). Cross symbol represent adjusted NDVI and corn grain yield mean using macroplot CV (%) mean. ** Significant at 1% level.

Planter Type Effect on Within-Row Plant Spacing

The planter types (TP and PP) in both experiments provided distinct within-row plant uniformity, as measured by the CV and SD of plant spacing (Table 2). The PP resulted in more uniform within-row plant spacing than TP (Table 2). However, the use of the RTK-based auto-steering system (APP), regardless of experiment, did not improve the uniformity of within-row plant spacing compared to PP (Table 2). Consequently, the uniformity of plant spacing will be addressed in this study by comparing the TP and PP planter types.

The final plant population was similar between planter types with between-row SD values of ± 3396 and ± 1529 plants ha^{-1} for TP and PP, respectively, in Exp. I. In Exp. II, the respective SD values for these treatments were ± 2003 and ± 995 plants ha^{-1} (Table 2).

Based on the target plant population (75,000), the average error for TP and PP was –3.1 and –1.8%, respectively, in the first experiment and +4.3 and +4.5%, respectively, in the second. Diverse factors such as soil temperature, soil moisture, depth of seed placement, seed vigor, physical damage caused to seeds, and pests affect the final plant population (Bullock et al., 1988; Thompson, 2013). In this study, both planter types were efficient in establishing the target plant population, but they exhibited distinct within-row uniformity with respect to plant spacing. Thus, regardless of experiment, PP had an average reduction of approximately 16.1% points in the CV of plant spacing in relation to TP (Table 2). Using a CV value ≤10% as the reference for within-row uniform plant spacing, no planter type was able to achieve the desired precision.

For TP, the CV of plant spacing was 4.1 and 3.6 times higher than the respective reference, while that for PP was 2.5 and 2.0 times higher in Exp. I and II, respectively (Table 2).

These results corroborate previously reported on-farm assessments of fields in southern Brazil, which reported that although the target plant population was achieved in most cases, the within-row plant spacing was non-uniform (Schimandeiro et al., 2006).

In the TP treatment in the first experiment, in addition to the high average CV of plant spacing, there was also a large CV amplitude (ranging from 30.4–52.8%) among the rows investigated, and in 30% of the rows, the CV was higher than 50%, that is, a value five times greater than that of the reference (Table 2). The magnitude of the CV was also high in PP (ranging from 15.7–34.1%). Generally, a high CV in plant spacing has been associated with a marked reduction in corn yield (Liu et al., 2004; Sangoi et al., 2012).

For the second experiment, regardless of planter type investigated, the plant spacing uniformity was superior to the first experiment, which may be explained by better distribution of rainfall during the post-seeding period compared to the first experiment, which had a 10-d drought period just after seeding (Fig. 2). Thus, regardless of treatment investigated in Exp. II,

Table 2. Macroplot of plant population, within-row plant uniformity expressed by CV and SD parameters of rows evaluated for traditional planting (TP), precision planting (PP), and auto-steering precision planting (APP) in the Exp. I and II.

Row	Plant population			CV			SD		
	TP	PP	APP	TP	PP	APP	TP	PP	APP
	plants ha^{-1}			CV			cm		
				Experiment I					
1	76,195.5	74,896.3	75,315.1	36.72	30.97	28.67	10	8	8
2	76,551.6	75,093.3	77,777.0	30.39	30.44	24.38	8	8	7
3	68,953.1	76,671.2	79,208.0	52.81	21.20	17.48	15	5	4
4	75,053.7	74,335.8	75,502.5	32.83	34.12	29.57	9	9	8
5	69,835.3	76,937.2	77,123.2	46.61	25.15	27.00	13	7	7
6	70,224.1	75,942.6	78,114.6	50.34	25.47	20.40	14	7	5
7	75,684.1	74,816.0	76,436.2	32.10	30.52	32.22	9	8	9
8	73,637.6	78,297.8	79,762.5	50.72	15.66	15.64	14	4	4
9	73,462.7	78,275.6	79,582.3	35.76	21.30	19.47	10	6	5
10	66,998.7	78,032.2	78,831.7	44.50	19.53	20.40	13	5	5
Mean	72,659.6	76,329.8	77,765.3	41.28	25.44	23.52	12	7	6
SE†	1,074.0	483.5	515.7	2.72	1.89	1.78	0.008	0.005	0.006
				Experiment II					
1	76,322.6	80,174.3	77,001.7	35.65	22.08	26.10	9	6	7
2	81,850.3	79,292.0	80,443.6	35.36	21.21	19.81	9	5	5
3	79,874.3	76,879.0	79,922.2	40.28	22.58	23.9	10	6	6
4	76,976.1	77,723.6	80,560.6	35.82	21.16	21.96	9	5	5
5	76,965.2	79,483.4	79,666.7	37.95	16.98	21.39	10	4	5
6	77,380.0	78,180.0	82,083.0	35.76	18.2	21.75	9	5	5
7	81,176.3	77,525.8	82,836.3	31.34	14.78	14.15	8	4	3
8	77,247.9	78,192.9	81,199.9	39.41	18.16	24.11	10	5	6
9	78,017.3	77,993.4	80,688.5	37.68	23.14	20.86	10	6	5
10	76,471.9	78,452.2	81,484.7	31.94	18.35	23.29	8	5	6
Mean	78,228.2	78,389.7	80,588.7	36.12	19.66	21.73	9	5	5
SE	633.5	314.6	501.7	0.91	0.87	1.02	0.002	0.002	0.003

† SE, standard error.

Table 3. Macroplot mean (standard error) of VI and corn grain yield for traditional planting (TP), precision planting (PP), and auto-steering precision planting (APP) in the Exp. I and II.

Treatment	Exp. I		Exp. II	
	VI	Grain yield	VI	Grain yield
		Mg ha^{-1}		Mg ha^{-1}
TP	6.07 (0.01)a†	9.95 (0.15)a	8.33 (0.04)a	6.99 (0.05)a
PP	6.56 (0.01)b	11.41 (0.04)b	8.24 (0.05)a	7.46 (0.08)b
APP	6.89 (0.01)c	12.20 (0.04)c	8.28 (0.04)a	7.44 (0.08)b
Mean	6.51	11.19	8.28	7.30

† Within a column for a given dependent variable, treatment means followed by the same letter are not significantly different (Tukey, α = 0.05).

more uniform plant spacing (lower CV) was achieved relative to Exp. I. However, even with favorable weather conditions (Exp. II), neither of the investigated rows in the TP treatment had CV < 30%. In contrast, 50% of the evaluations in the PP treatment had CV < 20%. No planter type reached the optimum plant spacing uniformity (<10%).

Vegetation Index and Corn Yield Affected by Within-Row Plant Spacing

The uniformity of plant spacing resulting from the treatments influenced the VI readings determined by N-Sensor in the first experiment but had no effect in the second experiment (Table 3). This result is consistent with the greater non-uniformity within-row plant spacing in the first experiment that was partially explained by the lack of precipitation after seeding. In the first experiment, TP resulted in the lowest VI among treatments; thus, the non-uniform within-row plant spacing decreased the VI by 13.5 and 8.1% in relation to APP and PP, respectively (Table 3).

There was a significant polynomial relationship between grain yield and VI in Exp. I (Fig. 4). The TP resulted in a higher frequency of plants with low VI (5.60–6.00), representing 33.6% of the investigated plants that also had lower grain yields. On the other hand, optimization of the within-row plant spacing resulted in plants with higher and more uniform nutritional plant status and higher grain yield (Fig. 4).

In Exp. I, a satisfactory distribution of rainfall at critical growth stages (Fig. 2) resulted in a mean grain yield of 11.19 Mg ha^{-1}, while in the second experiment, water stress at flowering decreased yield by 34.8% in relation to Exp. I. Under more favorable rainfall distribution, APP resulted in increases of

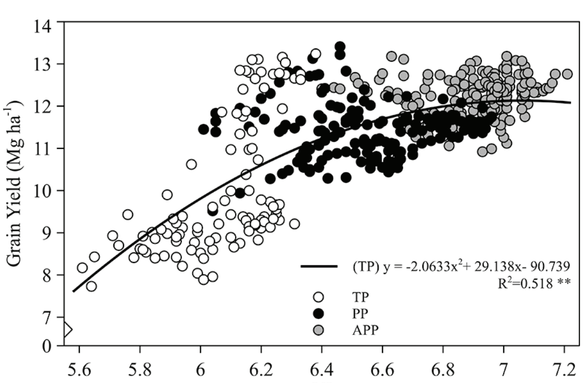

Fig. 4. Vegetation index (VI) and average corn grain yield for traditional planting (TP), precision planting (PP), and auto-steering precision planting (APP) for the first experiment (I). ** Significant at 1% level.

5.0 and 13.5% in the average VI compared to PP and TP, resulting in 6.9 and 22.6% increased grain yield, respectively (Table 3).

In this study, the improvement in the uniformity of plant spacing arrangement in the PP and APP treatments resulted in a higher VI and more uniform and higher corn grain yield in relation to TP (Fig. 4). Previously, Martin et al. (2005) reported that fields with high corn yield generally had plant growth uniformity that resulted in low yield variability across the cropland.

Thus, under weather conditions more favorable for crop growth, as in the first experiment, the APP treatment probably resulted in more accurate parallel rows that enhanced light, water and nutrient use, and even increased agrochemical efficiency and decreased corn harvest loss, resulting in higher grain yield (Table 3). On the other hand, under water stress (Exp. II) conditions, the APP treatment did not increase grain yield in relation to PP. Adoption of the auto-steering system during seeding operation is increasing in corn and soybean fields (Schimmelpfennig and Ebel, 2011) mainly because of grain yield gains and optimum fertilizer input (Bergtold et al., 2009; Griffin et al., 2008). The role of a guidance system in the uniformity of plant spacing and grain yield of grain crops should be elucidated in future research.

However, corn yield was higher with the planter equipped with the vSet devices and vacuum meter system, irrespective of experiment. A reduction of approximately 15.8 and 16.5% points in the CV of plant spacing in the PP treatment compared to the TP treatment (Table 2) resulted in corn yield increases of 14.7 and 6.7% in Exp. I and II, respectively (Table 3).

Therefore, the impact of uniform within-row plant spacing on yield was higher in the environment without water stress. This result is in contrast with the findings of DeLoughery and Crookston (1979) and Thompson (2013), who reported that the uniformity of plant spacing should be more critical in water-stressed environments. Regardless, the 12% increase in corn yield averaged over the 2 yr for the modern precision planting devices reinforces the need to focus on fine-tuning within-row plant spacing as a tool to improve crop yield.

Plant-to-Plant Study: Normalized Difference Vegetation Index and Grain Yield Influenced by Within-Row Plant Spacing

In general, the study performed in the microplots agreed with the macroplots but provided more detailed information on the impact of uniformity of plant spacing (Tables 3 and 4). The PP device decreased the CV of within-row plant spacing by 17.0 to 19.9% points in Exp. I and II, respectively, in relation to TP (Table 4). Similar to the above results, neither TP nor PP achieved the reference quality value in either experiment (CV < 10%).

Table 4. Microplot (plant-to-plant study) mean (SE) of plant spacing (CV), plant nutritional status (normalized difference vegetation index, NDVI) and corn grain yield for traditional planting (TP) and precision planting (PP) in the Exp. I and II.

	Exp. I			Exp. II		
Treatment	CV	NDVI	Grain yield	CV	NDVI	Grain yield
	%		Mg ha^{-1}	%		Mg ha^{-1}
TP	37.1 (3.91)a†	0.66 (0.009)a	10.63 (0.38)a	37.5 (2.83)a	0.71 (0.007)a	8.26 (0.23)a
PP	20.1 (2.48)b	0.73 (0.005)b	13.30 (0.28)b	17.6 (3.11)b	0.76 (0.005)b	9.29 (0.21)b

† Within a column for a given dependent variable, treatment means followed by the same letter are not significantly different (Tukey, α = 0.05).

The class frequency of within-row plant spacing under the different treatments investigated is present in Fig. 5. The target within-row plant spacing was 27 cm. The PP resulted in a frequency of plants in the optimal class (24–33 cm) that was 1.5 and 1.4 times higher in Exp. I and II, respectively, in relation to TP. In addition, in the TP treatment, 8.89 and 18.8% of the plants in Exp. I and II, respectively, had a spacing <18 cm (Fig. 5). However, compared to TP, the PP treatment reduced the frequency of plants with this low spacing by 2.6 and 3.2 times in Exp. I and II, respectively.

The close proximity of plants within rows increases competition for water, light, and nutrients, resulting in dominant plants and consequent decreases in corn yield. Nafziger (1996) reported that closely spaced plants had 17% lower yields than uniformly spaced plants for a plant population of 74,100 plants ha^{-1}. Thompson (2013) reported that the close proximity of plants within rows reduced kernel weight as the kernel number increased.

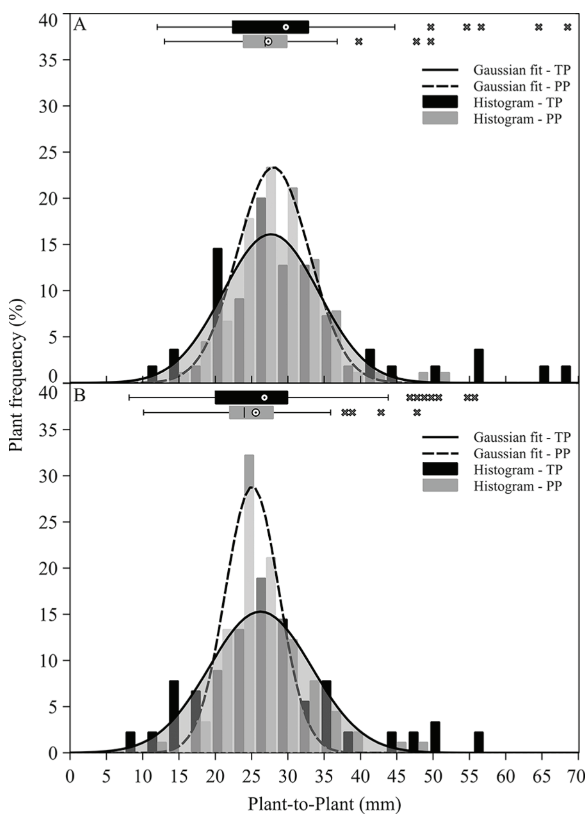

Fig. 5. Histogram with frequencies using 25 bins and overlaid with a normal density curve representing the distribution of plant spacing in the microplot for traditional planting (TP) and precision planting (PP) in (A) Exp. I and (B) Exp. II. Top part of graph are box-and whiskers plot. White circle is the mean of the distribution; the box extends around the quartile 2 and 3 (percentiles 25–75). Outliers are all x markers, and are considered as such if they are smaller than percentile 25–1.5 IQ. Whiskers extend between the smallest and the largest non-outlier values.

In the TP treatment in this study, 11.1 and 11.8% of plants had a plant spacing >39 cm in Exp. I and II, respectively, while for PP, these frequencies were reduced approximately 3.3- and 5.2-fold. Skipping plants resulted in the opposite effect to that observed for closely spaced plants, resulting in a plant grain yield increase of 9% higher than that measured under uniform plant spacing (Nafziger, 1996), but as the target plant population was compromised, a lower grain yield was measured in the field. In the first and second experiment, increases in the CV of plant spacing of 84.6 and 113.1% in response to TP relative to PP resulted in corn yield decreases of 20.1 and 11.1%, respectively (Table 4).

The within-row plant spacing distribution obtained in response to the treatments also influenced the NDVI readings determined by GreenSeeker in both experiments. In the plant-to-plant study, it was possible to more accurately investigate the relationship between NDVI and grain yield (Fig. 6).

Optimization of the within-row plant spacing in the PP treatment (Fig. 5) resulted in 82.2 and 90.0% of the plants with NDVI values >0.70 in Exp. I and II, respectively, and these plants also had higher grain yields (Fig. 6). On the other hand, the TP treatment resulted in 34.5 and 70.0% of plants with

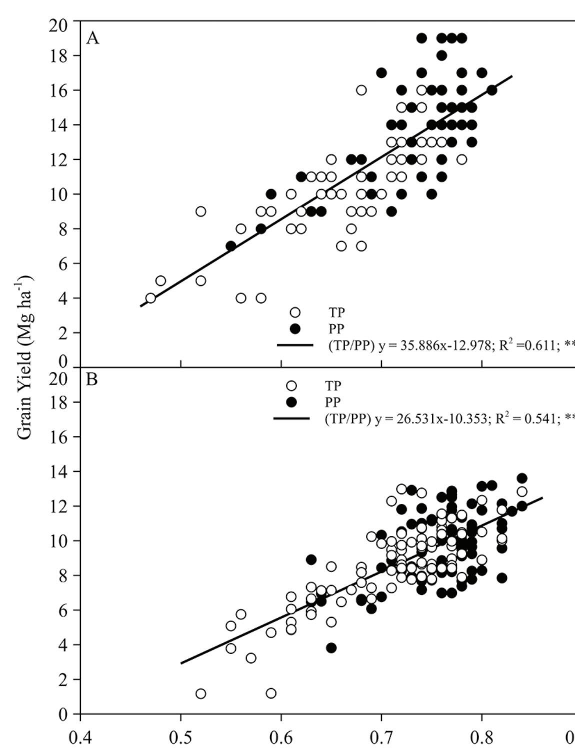

Fig. 6. Normalized difference vegetation index (NDVI) and average corn grain yield of the plant for traditional planting (TP) and precision planting (PP) in (A) Exp. I and (B) Exp. II in the microplot (plant-to-plant study). ** Significant at 1% level.

NDVI values >0.70. In a study performed in Oklahoma investigating this relationship at different growth stages, the strongest relationship between NDVI and grain and biomass yields (R^2 = 0.66) was found at the V8 growth stage (Martin et al., 2007). These results support the relationship between NDVI and grain yield found in our study. However, these authors found that the CV values based on the NDVI readings from the V7 to V9 growth stages were highly correlated with corn plant spacing ($R^2 > 0.85$, $p < 0.0001$). Uneven plant stands and missing plants resulted in lower NDVI readings (Raun et al., 2005), which is in agreement with our study.

The plant-to-plant study confirmed that non-uniform within-row plant spacing affected the corn nutritional status assessed using NDVI (Greenseeker) (Table 4), which is in agreement with the macroplots with respect to VI (N-Sensor) in the first experiment (Table 3). However, a more accurate relationship was established between plant spacing, nutritional status, and grain yield in the plant-to-plant study, as suggested by Martin et al. (2012) and Raun et al. (2005). This result was expected because the N-Sensor determined plant nutritional status based on an average value calculated from a group of plants in a 25-m^2 area, whereas the hand-held crop sensor was able to capture individual plant nutritional status and therefore showed better relationship with plant spacing uniformity.

The hand-held crop sensor was efficient in detecting the effect of dominant and dominated plants in relation to other strategies that have lower spatial resolution. This probably explains the observed relationship between NDVI and grain yield (Table 4) but not VI (Table 3) in Exp. II. In addition, in Exp. II, 27.8% of plants had a plant spacing <21 cm, which resulted in an increase in biomass per area when the N-Sensor was used (macroplots) but not the NDVI when individual plants were sensed using the GreenSeeker (plant-to-plant study).

The best plant spatial arrangement provided by PP in relation to TP, assessed in the plant-to-plant study, resulted in yield increases of 2.67 and 1.19 Mg ha^{-1} in the first and second experiment, respectively. Furthermore, corn plants in the PP treatment had, on average, 10.6 and 7.0% higher NDVI in the first and second experiment, respectively, compared with TP. In addition, in the PP treatment, 88.89% of the plants yielded >10 Mg ha^{-1} in the first experiment and 77.8% yielded >8 Mg ha^{-1} in the second experiment. As for TP, these plant frequencies were 60.0 and 67.8%, respectively (Fig. 6). Based on an average of the two experiments, the PP treatment resulted in a 47.6% increase in the frequency of plants with optimal plant spacing, increasing yield by approximately 16.4% compared with TP (Table 4). This result supports the recent technological efforts to develop devices for fine-tuning within-row plant spacing.

Nitrogen fertilization based on optical sensors that assess an average area or a group of plants can be enhanced when combined with precision plant technology based on the relationship between NDVI and grain yield (Fig. 6). By integrating information on plant spacing into N fertilizer prescription systems, the N recommendation for wheat (Arnall et al., 2006) and corn (Martin et al., 2012) was improved because the crop sensor was able to identify non-uniform within-row plant spacing that would not reach the yield potential. The lower CV of NDVI under uniform plant spacing increased the efficiency of the crop sensor in more accurately determining the plant nutritional status. In the current study, PP had a lower CV of NDVI compared with TP. Thus, optimizing within-row plant spacing may boost other precision farming strategies such as variable rate N fertilization (Raun et al., 2002) and may fine-tune the plant population by hybrid according to management zones (Hörbe et al., 2013).

The treatment with high technological devices for precision planting (vSet vacuum meter system) in the macroplot resulted in 25.4% CV of plant spacing (Table 2) and 11.41 Mg ha^{-1} grain yield in the first experiment (Table 3). Based on the equation shown in Fig. 3b, a 10% CV of plant spacing could result in approximately 28% yield increase in relation to PP. In the future, the enhancement of spatial plant arrangement should originate from new devices that will be equipped with high-tech planters, for example, downforce control on a row basis, perfect singulation and a steady stream of seeds, and orientation of seed deposition. With these new devices, a high level of precision planting (e.g., CV ≤ 10%) would be the target, allowing better exploration of hybrid genetic potential, recent improvements in inputs (fertilizer, agrochemicals) and improved soil husbandry (no-till and crop rotation).

CONCLUSIONS

Optimizing within-row plant spacing resulted in higher values of crop sensor readings (NDVI and IV), indicating improvement in plant nutritional status. There were negative linear relationships between within-row plant spacing error based on crop sensor readings and grain yield. In this study, on average, for every 16.15-percentage point increase in CV and 5-cm increase in the SD of plant spacing, there was a yield loss ranging from 0.47 to 1.46 Mg ha^{-1} according to the yield potential and range of CV plant spacing observed. Within-row plant spacing optimization obtained with the precision planter equipped with a vSet and vacuum meter system increased the average corn yield of the two experiments by 10.69% in relation to the traditional planter. In the year with more favorable rainfall distribution, use of the RTK-based auto-steering system associated with the precision planter resulted in a yield gain of 6.92% in relation to the precision planter without this system, supporting the integrated use of technologies (precision planter, auto-steering system and highly accurate signal).

The results indicate that the new high standard of precision plant spacing (CV < 10%), which was not achieved by the best planter types investigated (CV = 19.7%), would increase plant nutritional status and corn yield gains.

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REFERENCES

Amaral, L.R., J.P. Molin, G. Portz, F.B. Finazzi, and L. Cortinove. 2014. Comparison of crop canopy reflectance sensors used to identify sugarcane biomass and nitrogen status. Precis. Agric. 16:15–28. doi:10.1007/s11119-014-9377-2

Andrade, F.H., and P.E. Abbate. 2005. Response of maize and soybean to variability in stand uniformity. Agron. J. 97:1263–1269. doi:10.2134/agronj2005.0006

Arnall, D.B., W.R. Raun, J.B. Solie, M.L. Stone, G.V. Johnson, K. Girma et al. 2006. Relationship between coefficient of variation measured by spectral reflectance and plant density at early growth stages in winter wheat. J. Plant Nutr. 29:1983–1997. doi:10.1080/01904160600927997

Bergtold, J.S., R.L. Raper, and E.B. Schwab. 2009. The economic benefit of improving the proximity of tillage and planting operations in cotton production with automatic steering. Appl. Eng. Agric. 25:133–143.

Blackmore, S., R.J. Godwin, and S. Fountas. 2003. The analysis of spatial and temporal trends in yield map data over six years. Biosystems Eng. 84:455–466. doi:10.1016/S1537-5110(03)00038-2

Bragagnolo, J., T.J.C. Amado, R. da S. Nicoloso, J. Jasper, J. Kunz, and T. de G. Teixeira. 2013. Optical crop sensor for variable-rate nitrogen fertilization in corn: I- plant nutrition and dry matter production. Rev. Bras. Cienc. Solo 37:1288–1298. doi:10.1590/S0100-06832013000500018

Bullock, D.G., R.L. Nielsen, and W.E. Nyquist. 1988. A growth analysis comparison of corn grown in conventional and equidistant plant spacing. Crop Sci. 28:254–258. doi:10.2135/cropsci1988.0011183X002800020015x

Carlson, G., T. Doerge, and D. Clay. 2003. Estimating corn yield loss from unevenly spaced plants. Publ. SSMG-37. Int. Plant Nutrition Inst. http://www.ipni.net/publication/ssmg.nsf/0/53B768F32F21A844852579E50077C706/$FILE/SSMG-37.pdf (accessed 20 July 2015).

Chim, B.K., P. Omara, N. Macnack, J. Mullock, S. Dhital, and W. Raun. 2014. Effect of seed distribution and population on maize (*Zea mays* L.) grain yield. Int. J. Agron. 2014:1–8. doi:10.1155/2014/125258

CQFS-RS/SC. 2004. Manual de adubação e de calagem para o Estado do Rio Grande do Sul e Santa Catarina. Comissão de química e fertilidade do solo, Porto Alegre, RS, Brazil.

DeLoughery, R.L., and R.K. Crookston. 1979. Harvest index of corn affected by population density, maturity rating, and environment. Agron. J. 71:577–580.

Doerge, T., T. Hall, and D. Gardner. 2002. New research confirms benefits of improved plant spacing in corn. Crop insights 12. http://www.pioneer.com/usa/agronomy/corn/1202.htm (accessed 5 Nov. 2015) p. 1–5.

Durães, F.O.M., M.X. dos Santos, E.E.G. Gama, P.C. Magalhães, P.E.P. Albuquerque, and C.T. Guimarães. 2004. Fenotipagem associada à tolerância a seca em milho para uso em melhoramento, estudos genômicos e seleção assistida por marcadores. (In Portuguese.) Circular Técnica, no. 39. EMBRAPA, Sete Lagoas. http://www.agencia.cnptia.embrapa.br/recursos/Circular39 Fenotipagem associada a tolerancia.pdf (accessed 5 Nov. 2015).

Embrapa-Centro Nacional de Pesquisa de Solos. 2006. Sistema Brasileiro de classificação de solos. 2nd ed. Embrapa, Rio de Janeiro.

Griffin, T., D.M. Lambert, and J. Lowenberg-DeBoer. 2008. Economics of GPS enabled navigation technologies. In: R. Khosla, editor, Proceedings of the 9th International Conference of Precision Agriculture, Denver, CO. 20–23 July 2008. Colorado State Univ., Denver.

Hörbe, T.A.N., T.J.C. Amado, A.O. Ferreira, and P.J. Alba. 2013. Optimization of corn plant population according to management zones in Southern Brazil. Precis. Agric. 14:450–465. doi:10.1007/s11119-013-9308-7

ISO. 1984. Sowing equipment—Test methods. Part 1: Single seed drills (precision drills), 7256/1. Int. Organization for Standardization, Geneva, Switzerland.

Jasper, J., S. Reusch, and A. Link. 2009. Active sensing of the N status of wheat using optimized wavelength combination–impact of seed rate, variety and growth stage. In: E.J. Van Henten, D. Goense, and C. Lokhorst, editors, Proceedings of the 7th European Conference on Precision Agriculture, Wageningen, the Netherlands. 6–8 July 2009. Academic Publ., Wageningen, the Netherlands. p. 23–30.

Köppen, W. 1918. Klassifikation der Klimate nach Temperatur, Niederschlag und Jahresablauf (Classification of climates according to temperature, precipitation and seasonal cycle). Petermanns Geogr. Mitt. 64:193–203.

Liu, W., M. Tollenaar, G. Stewart, and W. Deen. 2004. Impact of planter type, planting speed, and tillage on stand uniformity and yield of corn. Agron. J. 96:1668–1672. doi:10.2134/agronj2004.1668

Maddonni, G.A., and M.E. Otegui. 2004. Intra-specific competition in maize: Early establishment of hierarchies among plants affects final kernel set. Field Crops Res. 85:1–13. doi:10.1016/S0378-4290(03)00104-7

Martin, K.L., K. Girma, K.W. Freeman, R.K. Teal, B. Tubańa, D.B. Arnall et al. 2007. Expression of variability in corn as influenced by growth stage using optical sensor measurements. Agron. J. 99:384–398. doi:10.2134/agronj2005.0268

Martin, K.L., P.J. Hodgen, K.W. Freeman, R. Melchiori, D.B. Arnall, R.K. Teal et al. 2005. Plant-to-plant variability in corn production. Agron. J. 97:1603–1611. doi:10.2134/agronj2005.0129

Martin, K., W. Raun, and J. Solie. 2012. By-plant prediction of corn grain yield using optical sensor readings and measured plant height. J. Plant Nutr. 35:1429–1439. doi:10.1080/01904167.2012.684133

Nafziger, E.D. 1996. Effects of missing and two-plant hills on corn grain yield. J. Prod. Agric. 9:238–240. doi:10.2134/jpa1996.0238

Nelson, D.W., and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In: D.L. Sparks et al., editors, Methods of soil analysis. Part 3. Chemical methods. 2nd ed. SSSA and ASA, Madison, WI. p. 961–1010.

Nielsen, R.L. 2004. Effect of plant spacing variability on corn grain yield. Purdue Univ., Lafayette, IN. www.agry.purdue.edu/ext/corn/research/psv/Update2004.html (accessed 10 July 2015).

Nielsen, R.L. 2001. Stand establishment variability in corn. Publ. AGRY-91-01. Dep. of Agronomy, Purdue Univ., Lafayette, IN. http://www.agry.purdue.edu/ext/pubs/AGRY-91-01_v5.pdf (accessed 15 July 2015).

Portz, G., J.P. Molin, and J. Jasper. 2012. Active crop sensor to detect variability of nitrogen supply and biomass on sugarcane fields. Precis. Agric. 13:33–44. doi:10.1007/s11119-011-9243-4

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815–820. doi:10.2134/agronj2002.8150

Raun, W.R., J.B. Solie, K.L. Martin, K.W. Freeman, M.L. Stone, G.V. Johnson, and R.W. Mullen. 2005. Growth stage, development, and spatial variability in corn evaluated using optical sensor readings. J. Plant Nutr. 28:173–182. doi:10.1081/PLN-200042277

Ritchie, S.W., J.B. Hanway, and G.O. Benson. 1993. How a corn plant develops. Iowa State Univ. of Sci. and Technol., Coop Ext. Serv. Spec. Rep. 48. Iowa State Univ., Ames.

Sangoi, L., A. Schmitt, J. Vieira, G.J. Picoli Júnior, C.A. Souza, R.T. Casa et al. 2012. Variabilidade na Distribuição Espacial de Plantas na Linha e Rendimento de Grãos de Milho. (In Portuguese, with English abstract.). Rev. Bras. Milho e Sorgo 11:268–277. doi:10.18512/1980-6477/rbms.v11n3p268-277

Sangoi, L., C. Schweitzer, P.R. Ferreira da Silva, A. Schmitt, V.P. Vargas, R. Trezzi Casa, and C. Arruda de Souza. 2011. Perfilhamento, área foliar e produtividade do milho sob diferentes arranjos espaciais. (In Portuguese, with English abstract.) Pesqi. Agropecu. Bras. 46:609–616. doi:10.1590/S0100-204X2011000600006

Sangoi, L., P.R.F. Silva, and G. Argenta. 2010. Estratégias de manejo do arranjo de plantas para aumentar o rendimento de grãos do milho. Graphel, Lages.

Sarlangue, T., F.H. Andrade, P.A. Calviño, and L.C. Purcell. 2007. Why do maize hybrids respond differently to variations in plant density? Agron. J. 99:984–991. doi:10.2134/agronj2006.0205

SAS Institute. 2016. SAS University edition. SAS Inst., Cary, NC.

Schimandeiro, A., P.H. Weirich Neto, L.M. Gimenez, M.J. Colet, and P.W. Garbuio. 2006. Distribuição longitudinal de plantas de milho (*Zea mays* L.) na região dos Campos Gerais, Paraná. (In Portuguese, with English abstract.). Cienc. Rural 36:977–980. doi:10.1590/S0103-84782006000300040

Schimmelpfennig, D., and R. Ebel. 2011. On the doorstep of the information age: Recent adoption of precision. USDA. Economic Res. Serv. Economic Information Bull. 80. http://www.ers.usda.gov/Publications/EIB80/ (accessed 20 Feb. 2014). p. 31.

Shearer, S.A., and S.K. Pitla. 2013. Precision planting and crop thinning. In: L. Stephen Young, E. George, and W.E.W. Meyer, editors, Automation: The future of weed control in cropping systems. Springer, Dordrecht, the Netherlands. p. 99–124. doi:10.1007/978-94-007-7512-1_6

Soil Survey Staff. 2010. Keys to Soil Taxonomy. 11th ed. Natural Resources Conserv. Serv., Washington, DC.

Staggenborg, S.A., R.K. Taylor, and L.D. Maddux. 2004. Effect of planter speed and seed firmers on corn stand establishment. Appl. Eng. Agric. 20:573–580. doi:10.13031/2013.17457

Tedesco, M.J., C. Gianello, C.A. Bissani, H. Bohnen, and S.J. Volkweiss. 1995. Análise de solo, plantas e outros materiais. Boletim Técnico no. 5. 2nd ed. Universidade Federal do Rio Grande do Sul, Porto Alegre.

Thompson, T.A. 2013. Within-row spacing effect on individual corn plant yield. Master diss. Univ. of Illinois, Urbana-Champaign.

Trimble, 2016. GreenSeeker handheld crop sensor-datasheet. Trimble Navigation Limited, Sunnyvale, CA. http://www.trimble.com/Agriculture/gs-handheld.aspx (accessed 13 July 2016).

Vieira, P.A., Junior., J.P. Molin, D. Dourado Neto, P.A. Manfron, L.S. Mascarin, G.D.C. Faulin, and E.R. Detomini. 2006. População de plantas e alguns atributos do solo relacionados ao rendimento de grãos de milho. (In Portuguese, with English abstract.) Acta Sci. Agron. 28:483–492. doi:10.4025/actasciagron.v28i4.780