Corn Response to Within Row Plant Spacing Variation

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ABSTRACT

Recent interest in establishing uniform spacing of corn (*Zea mays* L.) plants in the field has prompted many seed companies to offer planter-tuning services. Experiments were conducted in Wisconsin environments between 1999 and 2001 to investigate the response of corn to plant spacing variation (PSV). During 1999, adapted hybrids were grown in the field by overseeding and thinning to 37 000 and 74 000 plants ha^{-1} in a two-plant pattern with target PSV treatments of 0, 10.2, 20.3, and 30.5 cm and 0, 2.5, 5.1, 7.6, 10.2, and 12.7 cm, respectively. During 2000 and 2001, two-, four-, and eight-plant "hill" patterns were established with target PSV treatments of 5.1 and 10.2 cm; 5.1, 10.2, and 20.3 cm; 5.1 10.2, 20.3, and 30.5 cm standard deviation. The control treatment was a target PSV of 0 cm. In this study, PSV never affected plant lodging or grain test weight. In one of 24 environments grain moisture was significantly affected, but no relationship was observed with PSV. Grain yield was rarely affected by PSV in two-plant patterns. Relative grain yield was reduced up to 18% as plant spacing became more "hill-like" in two-, four-, and eight-plant patterns. Relative grain yield was reduced 1.06% cm^{-1} standard deviation as PSV increased above 12.0 cm. However, for most farmer field situations at current plant density recommendations, corn grain yield would not be affected by PSV, except when obvious hills are planted.

There is much recent interest in the grain yield response of corn (*Zea mays* L.) to plant spacing variation (PSV). Major seed companies offer planter "tuning" services and claim estimated yield improvements of 3 to 7% for properly tuned planters with uniform plant spacing over planters that establish corn stands with nonuniform spacing. Advertisements by other companies in trade publications claim yield increases up to 20% with well-tuned planters.

Key planting factors influencing corn stand establishment include spacing of seed, uniform seed depth, seed quality, planter speed, insects, diseases, desired seed density, and optimum soil environment for rapid germination and uniform emergence (including soil water and temperature). No single factor is responsible for differences among fields for stand establishment; rather, fields with uneven plant spacing have unique problems and often a combination of factors during the planting operation leads to inconsistent stands.

Previous results are mixed regarding corn grain yield response to PSV. Early research on PSV indicated little response to yield even when planted in hills (Kiesselbach et al., 1935 as reported by Dungan et al., 1958). In Iowa, no significant yield impacts were observed in stands with up to 15 cm standard deviation (Erbach et al., 1972).

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Similar results were observed in Ontario (Muldoon and Daynard, 1981), Illinois (Johnson and Mulvaney, 1980), and Indiana (Nielsen, 1995). Other results indicate increasing PSV significantly reduces grain yield. In Indiana, grain yield decreases 0.16 Mg ha^{-1} for each 2.5 cm standard deviation greater than the threshold of 5.1 cm (Nielsen, 1997). In Kansas, researchers found a 0.21 Mg ha^{-1} decrease for each 2.5 cm increase in PSV (Krall et al., 1977); others found that grain yield decreased when PSV values were greater than a threshold of 6.1 cm (Vanderlip et al., 1988).

Mixed results regarding grain yield response to PSV is related to plant density and the actual measurement of PSV. In the Kansas study (Krall et al., 1977), measurements were taken in fields with a minimum to maximum plant density of 47 400 to 64 600 plants ha^{-1} and plant density effects were confounded with PSV effects. Gaps have more of an effect on grain yield than doubles (Johnson and Mulvaney, 1980). Gaps and doubles tend to have their effects on grain yield in opposite directions (Nafziger, 1996). These inconsistent responses cannot be attributed to yield level, irrigation, hybrid, or soil type (Vanderlip et al., 1988).

Clearly the importance of uniform stands is not resolved in the literature. Most farmers and agronomists agree that uniform stand establishment is ideal and can only be achieved by a well-calibrated planter and sound agronomic practices. Our objective was to measure the response of corn to PSV, and, if a response was significant, to determine the threshold where PSV affects grain yield.

MATERIALS AND METHODS

Background information was collected on stand uniformity in Wisconsin commercial corn fields during 1998, 1999, and 2000. University of Wisconsin County Extension faculty evaluated stand uniformity in a total of 127 production fields across 19 counties. Plant to plant spacing was measured between 30 consecutive corn plants for every row unit of the planter at two different sites within each field evaluated. Fields and areas of fields were selected that had good emergence so that factors other than planter performance (e.g., diseases, insects, and environmental conditions) were minimized. Stand uniformity was characterized by determining plant spacing standard deviation, plant density, average plant spacing, row gaps per 15.2 m, and seed doubles per 15.2 m. Plant doubles were defined as any plants within 5.1 cm of each other. Gaps for 76- to 97-cm row spacings were defined as spaces of 30.5 cm or more without an emerged plant. For 51-cm row spacings, gaps were defined as 46 cm or more without a plant. Field owners were surveyed to obtain background information about each field.

Replicated PSV studies were conducted in 24 environments between 1999 and 2001. In all years, the adapted hybrids used were 'Pioneer Brand 35R57' planted at Arlington, Janesville, and Lancaster; 'Cargill Brand 4111' planted at Fond du Lac, Galesville, and Hancock; and 'Novartis NK Brand 3030Bt' planted at Chippewa Falls, Marshfield, Seymour, and Valders. Management practices were typical of those utilized commer-

Abbreviations: PSV, plant spacing variation.

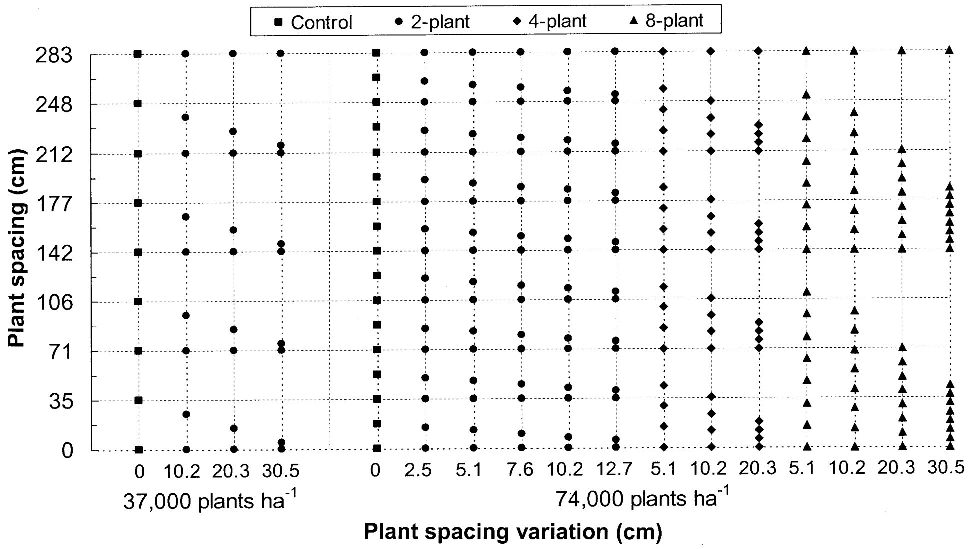

Fig. 1. Target plant spacing variation (PSV) treatments for two-, four-, and eight-plant patterns for plant densities of 37 000 and 74 000 plants ha^{-1}. The control is zero PSV.

cially in many dryland fields in the Corn Belt of the Midwestern USA. Preplant soil samples from the 0- to 15-cm depth were analyzed for residual nutrient levels. Soil was sampled from a field where the previous crop was usually either corn or soybean [*Glycine max* (L.) Merr.]. Adequate N was applied and a starter fertilizer (6–24–24) was applied 5 by 5 cm at planting. The soil in the study areas was prepared for seeding by fall chiseling and spring soil finishing. A Kinze planter (Kinze Manufacturing, Williamsburg, IA) was used to seed in furrows 5 cm deep. Plots were 6.7 m long and four rows wide in a row spacing of 76 cm. Weeds were controlled using pre- and/or postemerge herbicides and varied with environment. In addition, plots were hand weeded to control escape weeds. Plots were harvested in mid- to late-October.

The experimental design in each environment was a randomized complete block with three replications. The PSV treatments were established by over seeding at 222 400 seeds ha^{-1} and thinning back at V5-6 (Ritchie et al., 1993) to desired PSV treatments. In 1999, a total of 10 PSV treatments were established in target plant densities of 37 000 and 74 000 plants ha^{-1}. For 37 000 plants ha^{-1}, PSV treatments of 0, 10.2, 20.3, and 30.5 cm standard deviation were established at thinning; and for 74 000 plants ha^{-1}, treatments of 0, 2.5, 5.1, 7.6, 10.2, and 12.7 cm standard deviation. The 0 PSV treatment was considered the control. The PSV treatments (Fig. 1) were accomplished by selecting the neighbor plant closest to the target spacing and removing all plants between selected neighbors (two-plant pattern).

In 2000 and 2001, only the target plant density of 74 000 plants ha^{-1} was used. A total of 10 PSV treatments were established. In addition to the two-plant pattern involving neighboring plants, additional four- and eight-plant patterns were established (Fig. 1) where four- and eight-plant "hills" of plants were separated by a gap. The four- and eight-plant patterns were established to increase the number of PSV treatments greater than 10.2 cm. The control treatment was a PSV of 0 cm. The two-plant pattern had PSV treatments of 5.1 and 10.2 cm standard deviation; the four-plant pattern had treatments of 5.1, 10.2 and 20.3 cm standard deviation; and the eight-plant pattern had treatments of 5.1 10.2, 20.3, and 30.5 cm standard deviation.

The PSV is defined as the standard deviation of the distance between neighboring plants and was measured for each plot at harvest. Stalk lodging was recorded before harvest and expressed as a percentage of the final stand. Plants were considered lodged when broken below the ear and/or leaning more than 45° from vertical. Grain yield, moisture content, and test weight were automatically measured using a GrainGage linked to a HarvestData system (Juniper Systems, Logan, UT) mounted on a two-row Kincaid plot combine (Kincade Equipment Manufacturing, Haven, KS). Test weights are reported at harvest moisture.

For each environment and target plant density, the data measured for PSV, grain yield, plant lodging, grain moisture and grain test weight were analyzed using the GLM procedure (SAS Inst., 2000) with harvested plant density used as a covariate. Grain yield was further analyzed using the REG procedure to determine the relationship between grain yield and PSV for each environment. Linear and quadratic coefficients were calculated using the STEPWISE selection method in REG and were required to be significant at $P \leq 0.05$ to stay in the model. Lastly, relative grain yield was calculated by dividing the yield of each plot by the average of the highest yielding PSV treatment for each target plant density and environment. Relative grain yield could then be combined across all environments. Treatment means for each environment were used for all regression analyses. The control was used in the analysis of each plant pattern. Five response models (linear, quadratic, plateau-linear segmented, plateau-quadratic segmented, and exponential) were tested by fitting combined data using REG or NLIN procedures.

RESULTS AND DISCUSSION

In the survey conducted on 127 Wisconsin commercial corn fields, the average target seeding rate was 75 400 plants ha^{-1} (Table 1). The actual stand that emerged was 73 500 plants ha^{-1} for an average stand as planted of 97% (min. = 78% to max. = 121%). The PSV average was 8.4 cm (min. = 4.8 to max. = 17.3 cm). Within these commercial corn fields, 95% of the surveyed fields had PSV less than 11.7 cm. The average number of seed doubles was 0.36 m^{-1} of row, while average number of gaps was 0.46 m^{-1} of row. Doubles and gaps were minor in most stands and would not likely affect grain yield. Most spacing variation occurred between neighboring plants (i.e., two-plant pattern).

Table 1. Stand characteristics of Wisconsin commercial corn fields evaluated for stand uniformity during 1998–2000 ($n = 127$).

Measurement	Avg.	SD	Min.−max.
Target seeding rate, seeds ha^{-1}	75 400	6900	51 900–103 800
Actual plant density, plants ha^{-1}	73 500	8600	54 200–110 200
Plant spacing variation, cm	8.4	2.1	4.8–17.3
Number of doubles m^{-1}, neighbor plants <5.1 cm	0.36	0.36	0.01–1.7
Number of gaps m^{-1}, neighbor plants >30.5 cm	0.46	0.02	0.07–1.1

The PSV adequately describes uniform vs. nonuniform plant stands; however, the term does not always convey a meaningful assessment of stand uniformity problems. Within-row gaps influenced PSV more than doubles. The PSV is also inherently higher as row spacing and/or target plant density decreases due to more space between two neighboring plants. Thus, comparing PSV as a measure of stand variability may only be useful where row spacing and plant densities are similar. Care was taken to ensure that plant density among PSV treatments within an environment was equal.

In 1999, plant density treatments significantly affected all agronomic measures, and thus PSV treatments were analyzed within each plant density level. The plant density range between PSV treatments in an environment was 900 to 3500 plants ha^{-1} and 1400 to 8400 plants ha^{-1} for plant density treatments of 37 000 and 74 000 plants ha^{-1}, respectively. Within these target plant densities, no significant differences between PSV treatments were observed for plant density in 17 of 20 cases, indicating that similar plant density was achieved between PSV treatments. In the 3 of 20 cases where plant density was significantly different among PSV treatments, plant densities were within 900 to 5500 plants ha^{-1} indicating that yields might be affected at most by about 2% due to changes in plant density (Lauer, 1997). The only way to increase PSV in a plant community and not affect plant density is to arrange plants into hill patterns (Fig. 1).

During 2000 and 2001, plant density was affected by PSV treatments in 6 of 14 environments. The plant density range between PSV treatments was 5000 to 15 700 plants ha^{-1}. Of the environments with a range more than 7400 plants ha^{-1} between PSV treatments (10% of the target stand of 74 000 plants ha^{-1}), grain yield was not affected in four of eight environments. Also, some plant death was observed in four- and eight-plant "hills," thereby affecting final harvest plant density.

During 1999, the range among PSV treatments within an environment was 13.1 to 23.6 cm and 3.1 to 4.6 cm standard deviation for the plant density treatments of 37 000 and 74 000 plants ha^{-1}, respectively. Significant differences among PSV treatments were observed in 19 of 20 environments, indicating that thinning of plants to establish PSV treatments was successful.

In 2000 and 2001, one plant density (74 000 plants ha^{-1}) in two-, four-, and eight-plant hills was established. The range among PSV treatments within an environment was 18.1 to 28.5 cm.

It was difficult to establish a control treatment with a target PSV of 0 cm. In this study the control treatments ranged from 4.18 to 8.33 cm standard deviation. Many reasons can be attributed to this including slight deviation from the mark at thinning, change in plant size between thinning and when spacing measurements were taken at harvest, and measurement error all could affect target PSV.

Table 2. Analysis of variance significance for plant spacing variation (PSV) experiments conducted in Wisconsin during 1999. Two plant densities were arranged in a plant spacing deviation using a two-plant pattern.

Environment	PSV	Grain yield	Grain moisture	Plant lodging	Grain test wt.
		37 000 plants ha^{-1}			
Arlington	*	NS	NS	NS	NS
Janesville	**	NS	NS	NS	NS
Lancaster	**	NS	NS	NS	NS
Fond du Lac	**	NS	NS	NS	NS
Galesville	**	*	NS	NS	NS
Hancock	**	NS	NS	NS	NS
Chippewa Falls	**	NS	NS	NS	NS
Marshfield	**	NS	NS	NS	NS
Seymour	**	NS	NS	NS	NS
Valders	**	NS	NS	NS	NS
		74 000 plants ha^{-1}			
Arlington	**	NS	NS	NS	NS
Janesville	**	NS	NS	NS	NS
Lancaster	NS	NS	NS	NS	NS
Fond du Lac	*	NS	NS	NS	NS
Galesville	*	NS	*	NS	NS
Hancock	**	NS	NS	NS	NS
Chippewa Falls	**	NS	NS	NS	NS
Marshfield	**	NS	NS	NS	NS
Seymour	**	NS	NS	NS	NS
Valders	**	NS	NS	NS	NS

* Significance at the $P \leq 0.05$ level.
** Significance at the $P \leq 0.01$ level.

During 1999, PSV treatments affected grain yield in 1 of 20 cases (Table 2). In the single case where grain yield was significantly affected, the PSV treatment of 10.2 cm was greater than the control. Grain moisture was affected by PSV in 1 of 20 cases. No trend was observed between PSV and grain moisture. Plant lodging and grain test weight were not affected by PSV treatments. Thus, there was little evidence to support the hypothesis that PSV affects grain yield or other agronomic measures in a two-plant pattern as long as plant density is similar among PSV treatments.

During 2000 and 2001, increasing PSV by arranging plants in a two-, four-, and eight-plant patterns increased the number of environments where grain yield was significantly affected (Table 3). Grain yield was affected by

Table 3. Analysis of variance significance for two-, four-, and eight-plant pattern spacing variation (PSV) experiments conducted in Wisconsin during 2000 and 2001. Target plant densities were 74 000 plants ha^{-1}.

Environment	Year	PSV	Grain yield	Grain moisture	Plant lodging	Grain test wt.
Arlington	2000	**	**	NS	NS	NS
	2001	**	NS	NS	NS	NS
Janesville	2000	**	NS	NS	NS	NS
	2001	**	**	NS	NS	NS
Lancaster	2000	**	NS	NS	NS	NS
Fond du Lac	2000	**	*	NS	NS	NS
	2001	**	NS	NS	NS	NS
Galesville	2000	**	**	NS	NS	NS
	2001	**	*	NS	NS	NS
Hancock	2000	**	**	NS	NS	NS
Chippewa Falls	2000	**	NS	NS	NS	NS
Marshfield	2000	**	NS	NS	NS	NS
Seymour	2000	**	**	NS	NS	NS
Valders	2000	*	**	NS	NS	NS

* Significance at the $P \leq 0.05$ level.
** Significance at the $P \leq 0.01$ level.

Table 4. Relationship between grain yield (y) and plant spacing variation (x) for a two-plant pattern treatment grown at 37 000 and 74 000 plants ha^{-1} in Wisconsin during 1999.

Environment	37 000 plants ha^{-1} Avg. grain yield	Model	R^2	74 000 plants ha^{-1} Avg. grain yield	Model	R^2
	Mg ha^{-1}			Mg ha^{-1}		
Arlington	10.6	$y = 10.1 + 0.029x$	0.97	15.2	$y = 14.7 + 0.007x^2$	0.79
Janesville	10.8	NS†	–	15.0	NS	–
Lancaster	9.0	NS	–	12.1	NS	–
Fond du Lac	11.2	NS	–	14.3	NS	–
Galesville	8.3	NS	–	11.7	NS	–
Hancock	9.9	NS	–	13.3	NS	–
Chippewa Falls	9.6	NS	–	11.6	NS	–
Marshfield	8.9	NS	–	12.1	NS	–
Seymour	10.3	NS	–	13.6	$y = 15.1 - 0.169x$	0.73
Valders	10.4	NS	–	13.8	$y = 13.4 + 0.007x^2$	0.71

† NS = no significant ($P \leq 0.05$) term stayed in the model.

PSV in 8 of 14 environments. However, the other agronomic measures of grain moisture, plant lodging, and grain test weight were not affected by increasing PSV.

During 1999, grain yields ranged among the environments from 8.3 to 11.2 Mg ha^{-1} for 37 000 plants ha^{-1} and from 11.6 to 15.2 Mg ha^{-1} for 74 000 plants ha^{-1} (Table 4). Linear and quadratic relationships between grain yield and PSV were observed in 4 of 20 cases. In three of four cases grain yield increased with increasing PSV, while in the fourth case grain yield decreased with increasing PSV.

During 2000 and 2001, average grain yields among the environments ranged from 9.0 to 14.4 Mg ha^{-1} (Table 5). For the two-plant pattern treatments, none of the 14 environments had a significant relationship between grain yield and PSV. As PSV increased with four- and eight-plant arrangements more environments exhibited significant linear and or quadratic relationships. For four-plant patterns, 2 of 14 environments had a significant relationship between grain yield and PSV, and for eight-plant patterns, 11 of 14 environments had significant relationships. In all cases where a significant relationship was measured, grain yield decreased with increasing PSV.

Treatment mean data from all environments were combined and five model forms were investigated to describe the relationship between grain yield and PSV (Table 6). There was little difference between models within a plant pattern. For two-plant patterns, R^2 values were low, indicating a poor relationship between grain yield and PSV. For four- and eight-plant patterns, R^2 values for all model forms increased. When all plant patterns were included in the models the quadratic, plateau-linear segmented, and plateau-quadratic segmented model forms gave the highest R^2 values. Since previous workers (Krall et al., 1977; Vanderlip et al., 1988; Nielsen, 1997) have described the relationship between grain yield and PSV as significant above some threshold, the plateau-linear segmented model was chosen to describe the relationship (Fig. 2).

The data for each plant pattern were analyzed using a Plateau–Linear segmented model. The model for the four-plant pattern was $y = 96.3$, if $x \leq 9.5$ cm and $y = 100.8 - 0.475x$, if $x > 9.5$ cm ($R^2 = 0.19$), where y is relative grain yield and x is PSV. The eight-plant pattern model was $y = 96.0$, if $x \leq 11.8$ cm and $y = 108.7 - 1.08x$, if $x > 11.8$ cm ($R^2 = 0.66$). The 95% confidence interval around the threshold value for the four- and eight-plant pattern models was 3.5 to 15.5 cm and 8.2 to 15.5 cm.

The overall relationship between relative grain yield and PSV is shown in Fig. 2. The threshold value for the overall relationship was 12.0 cm and the 95% confidence interval was 9.9 to 14.1 cm. Grain yield was not affected from that of the control when all plant patterns had PSV less than 12 cm, but grain yield was reduced between 5

Table 5. Relationship between grain yield (y) and plant spacing variation (x) for two-, four-, and eight-plant pattern treatments grown at 74 000 plants ha^{-1} in Wisconsin during 2000 and 2001.

Environment	Year	Avg. grain yield	Two-plant pattern Model	R^2	Four-plant pattern Model	R^2	Eight-plant pattern Model	R^2
		Mg ha^{-1}						
Arlington	2000	12.5	NS†	–	$y = 13.4 - 0.004x^2$	0.93	$y = 13.7 - 0.095x$	0.94
	2001	12.7	NS	–	$y = 13.0 - 0.002x^2$	0.99	NS	–
Janesville	2000	11.6	NS	–	NS	–	$y = 12.0 - 0.002x^2$	0.97
	2001	14.4	NS	–	NS	–	$y = 14.2 + 0.151x - 0.010x^2$	1.00
Lancaster	2000	10.5	NS	–	NS	–	NS	–
Fond du Lac	2000	10.1	NS	–	NS	–	$y = 11.0 - 0.061x$	0.89
	2001	9.2	NS	–	NS	–	$y = 9.54 - 0.002x^2$	0.89
Galesville	2000	9.5	NS	–	NS	–	$y = 10.7 - 0.005x^2$	0.90
	2001	11.6	NS	–	NS	–	$y = 12.5 - 0.081x$	0.93
Hancock	2000	10.1	NS	–	NS	–	$y = 10.3 - 0.002x^2$	0.89
Chippewa Falls	2000	9.3	NS	–	NS	–	$y = 9.67 - 0.003x^2$	0.94
Marshfield	2000	10.7	NS	–	NS	–	$y = 11.3 - 0.003x^2$	0.99
Seymour	2000	10.3	NS	–	NS	–	$y = 10.6 - 0.003x^2$	0.85
Valders	2000	9.0	NS	–	NS	–	NS	–

† NS = no significant ($P \leq 0.05$) term stayed in the model.

Table 6. Coefficients of determination (R^2) of various model forms describing the relationship between relative grain yield and plant spacing variation. Values used were environment × treatment means.

Plant density	Pattern	Linear	Quadratic	Plateau–linear	Plateau–quadratic	Exponential
plants ha^{-1}						
37 000	two-plant	0.00	0.10	0.06	0.07	0.04
74 000	two-plant	0.01	0.09	0.00	0.08	0.09
74 000	four-plant	0.16	0.23	0.19	0.22	0.23
74 000	eight-plant	0.62	0.64	0.66	0.67	0.63
74 000	all	0.53	0.57	0.57	0.57	0.54

and 18% as PSV increased above 12 cm standard deviation when obvious gaps where present in the stand and plants were arranged in four- and eight-plant patterns.

In the Wisconsin survey, 95% of the planters evaluated in 127 fields had PSV below the threshold described in Fig. 2. Several factors influence a plant's ability to compete among individuals within a plant community. Agronomic production of crops usually involves homogeneous individuals that theoretically compete equally for resources so that exclusion at the community level rarely occurs. Yet, variation exists, especially for yield, the ultimate integrator and measure of a plant's ability to compete for resources. Some variation in grain yield can be traced to plant density, plant spacing relative to neighbors, time of emergence, and developmental setbacks due to pests and weather. At least two types of plant variation are usually observed in the field that can occur alone and in combination. First is *plant spacing variation at the same plant density*. This is usually observed after planting with an improperly set up planter. Second, excessive planting speed, crusting, "thickening-up" of stands, dry soils, and so forth can cause *plant temporal variation*. This latter type of variation may be most important in the field.

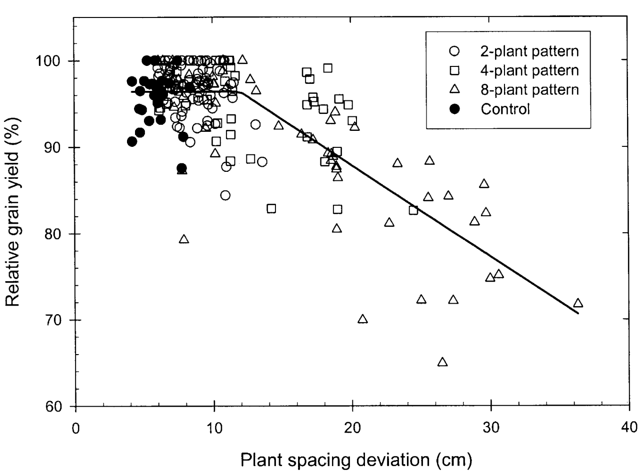

Fig. 2. Relationship between relative grain yield and plant spacing variation (PSV) for two-, four-, and eight-plant patterns at 74 000 plants ha^{-1} ($y = 96.4$, if $x < 12.0$ and $y = 109.1 - 1.06x$, if $x > 12.0$; $R^2 = 0.57$). Relative grain yield was determined for each plot as yield divided by the average yield from the greatest yielding PSV treatment for each environment.

CONCLUSIONS

In this study using a plant density typically found in commercial production fields, relative grain yield decreased 1.06% for every 1 cm standard deviation greater than 12 cm standard deviation. To achieve PSV in this range at modern plant densities, plant patterns would need to consist of numerous gaps and "hills" of two (double) to eight plants. These plant patterns would be obvious and are certainly atypical of current production practices.

In light of these results, do planters need to be tuned? Agronomists should never recommend not going through and tuning a planter because it provides "peace of mind" and planter problems can be corrected before the planting season begins. However, the corn plant can compensate dramatically to PSV as long as plant density is adequate in the field. What might be more important is temporal variation for time of plant emergence. Temporal and seeding depth variation in corn stands need to be further researched.

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