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Economic optimum plant density of sweet corn does not increase root lodging incidence

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Abstract

Exploitation of plant density tolerance in sweet corn (*Zea mays* L.), including the use of density-tolerant hybrids at plant densities that optimize economic returns (hereafter called economic optimum plant density), has the potential to improve profitability. Multiple experimental approaches, including artificially created root lodging events in field trials and natural root lodging events in growers' fields, were used to determine if economic optimum plant densities, compared with current plant densities, increase incidence of root lodging in sweet corn. An artificially created root lodging experiment over multiple years showed the environment in which sweet corn is grown is far more important to the effects of root lodging than plant density. In trials with natural root lodging events, results showed commercial sweet corn hybrids differed greatly in their susceptibility to root lodging, with some cultivars tolerant across all plant densities. Across 16 experimental comparisons of sweet corn response to plant density where natural root lodging was observed, including seven environments and 11 commercial hybrids, there was no difference in root lodging between current and economic optimum plant densities. Factors other than plant density dominate the crop's potential for, and recovery from, root lodging in growers' fields, namely, the hybrid and the environment in which the crop is grown.

1 | INTRODUCTION

Root lodging is a structural failure of the root–soil anchorage system of the plant. It is a complex phenomenon influenced largely by crop genetics and environmental conditions. Root lodging caused by rain and windstorms can be a significant problem in all types of maize (*Zea mays* L.) including grain production (i.e., field corn) or specialty types (e.g., sweet corn). Root lodging is a mechanical process where the bending moment caused by wind on the plant shoot exceeds the resistance of the root–soil anchorage system (Baker et al., 2014; Brune et al., 2017). A portion of the root base rotates irreversibly, moving the plant off its vertical alignment. Sometimes natural lodging events are used to phenotype field corn lodging (Bruce et al., 2001; Farkhari et al., 2013). The ability of the corn plant to straighten itself through phototropism (hereafter called plant recovery) and impact on crop yield is influenced greatly by crop growth stage at the time of the root lodging event (Carter & Hudelson, 1988). Root lodging during pollination or later results in significant grain losses (Carter & Hudelson, 1988; Nielsen, 2002). Across a diverse field corn germplasm collection, a negative relationship was observed between root lodging and grain yield (Mansfield & Mumm, 2014).

Several factors influence root lodging incidence in field corn. Reduced root systems and lodging susceptibility due to soilborne pests have received considerable study (e.g., Novacek et al., 2014; Sutter et al., 1990). Soil compaction and adverse weather, particularly temperature and rainfall anomalies, can compromise root development. Field corn cultivars differ in susceptibility to root lodging (Farkhari et al., 2013). Certain aspects of crop management's role in root lodging have been studied, including crop row configuration and plant density (Liu et al., 2012; van Roekel & Coulter, 2012).

Historically, plant density has played an important role in improving yield of field corn (Duvick, 2005). Modern field corn hybrids yield more than their predecessors, in large part because of improved plant density tolerance and increasing plant densities (Tollenaar & Lee, 2002). Recent research has revealed new opportunities for plant density to improve sweet corn production as well. In sweet corn grown for processing, hybrids differ widely in plant density tolerance (Williams, 2012; 2015). Recent on-farm research confirms that density-tolerant hybrids were being underplanted in the United States and that optimizing plant density for economic return of such hybrids improves profitability to both growers and processors (Dhaliwal & Williams, 2019). Like field corn a half-century ago, the sweet corn industry is now beginning to exploit plant density tolerance, including seed companies developing germplasm with improved plant density tolerance (Quinn, 2019).

As the sweet corn industry transitions to the use of density-tolerant hybrids planted at densities that optimize their profitability, could root lodging occur more frequently? Primary research on root lodging in sweet corn is nearly nonexistent and there are no published studies on the role of plant density in root lodging. However, phenotyping a crop's root lodging potential is inherently difficult. The erratic nature of climatic conditions inducing root lodging makes it difficult to study the phenomenon in the field or, in the case of a breeding program, achieve a rapid selection process (Fouéré et al., 1995; Mansfield & Mumm, 2014). Simply put, a natural root lodging event may not happen in any given field experiment. As such, phenotyping crops for root lodging often uses artificially created lodging events (Carter & Hudelson, 1988; Liu et al., 2012). In these studies, supplemental water often is used to saturate the soil profile and manual pushing of the plants is used to mimic wind load. Although artificially created root lodging events are helpful, used alone they often fail to capture a broad range of environments in which the crop is grown.

To determine if density-tolerant sweet corn hybrids planted at densities that optimize their profitability increase incidence of root lodging, we used multiple experimental approaches including artificially created root lodging events in field trials and natural lodging events in growers' fields. The objectives of the research in sweet corn were (a) to determine the extent to which root lodging at tasseling influences plant recovery and yield response to plant density and (b) to quantify the extent to which increasing plant density from current to economic optimum densities for sweet corn increases root lodging severity from natural lodging events.

Core Ideas

- Optimizing economic plant density of density-tolerant sweet corn improves profitability.
- Environment and hybrid have much greater effect on root lodging than plant density.
- Compared with current plant density, economic optimum plant density does not increase root lodging incidence.

2 | MATERIALS AND METHODS

Our first objective was addressed by conducting a field experiment in sweet corn in which root lodging was artificially created across a range of plant densities in multiple environments. Recovery from root lodging and yield were measured. Our second objective was addressed by scoring the severity of root lodging in separate plant density experiments where natural lodging events occurred during the growing season. A complete accounting for soil–root dynamics was not the focus of this research but rather addressing the practical question of economic optimum plant density effect on the hazards of root lodging, including incidence of and effects from root lodging. Details of all experimental procedures are described below.

2.1 | Artificially created root lodging experiment

Field experiments were conducted in 2016 and 2017 at the University of Illinois's Vegetable Crop Research Farm near Urbana, IL. A different field was used each year, whereby the preceding crop was soybean [*Glycine max* (L.) Merr.]. The soil was a Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls) averaging 3.7% organic matter and a pH of 5.7. Prior to planting, 135 kg N ha^{-1} was applied as urea-ammonium nitrate 28% and incorporated with a field cultivator. Sweet corn ('DMC 21-84′) was planted on 76-cm rows oriented north–south on 16 May both years. Hybrid DMC 21-84 has superior plant density tolerance relative to 25 other commercial shrunken-2 endosperm processing hybrids (Williams, 2015). At the time of this study, DMC 21-84 was the single most widely grown hybrid by a leading U.S. vegetable processor (Williams, unpublished data). Other density tolerant hybrids (e.g., GG 641) are widely grown by other leading vegetable processors (Williams, 2015). Tefluthrin ([2,3,5,6-tetrafluoro-4-methylphenyl]methyl [1R,3R]-rel-3-[{1Z}−2-chloro-3,3,3-trifluoro-1-propenyl] −2,2-dimethylcyclopropanecarboxylate) was applied in a t-band at planting to control corn rootworms (*Diabrotica* spp.). A preemergence treatment of *s*-metolachlor (2-chloro-N-[2-ethyl-6-methylphenyl]-N-[{1S}−2-methoxy-1 -methylethyl]acetamide) plus atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine) was applied after planting. Weeds escaping control from herbicides were removed by hand or hoe, as needed.

2.2 | Experimental approach

The experimental design of the artificially created root lodging experiment was a split plot arrangement within a randomized complete block with four replications. Main plot treatment was assigned plant density; namely 4.3, 5.7, 7.2, 8.6, or 10.1 plants m^{-2} on 76-cm rows. Based on surveys of growers' fields, current plant density averages 5.6 plants m^{-2} (Williams, 2012; 2018). Plant densities were established by overseeding each treatment 25% and hand-thinning within the row as close as possible to the target plant density when plants had two visible leaf collars. The 3-m-wide main plots consisted of four crop rows and were divided into two 9.1-m-long subplots of four rows. Subplot treatments were assigned one of two lodging treatments, namely, root lodging or none. Root lodging conditions were created at tasseling (VT growth stage, defined by Ritchie et al., 1993) by supplementing rainfall with irrigation, up to 5.0 cm of water, to fully saturate the upper 20 cm of soil. When root lodging was created, gravimetric soil water content was 23.3 and 22.8% in 2016 and 2017, respectively. A 4-cm × 9-cm wooden board, 3.4 m in length, was placed parallel to and against the corn row 30 cm above the soil surface. Two people applied force laterally to the board until corn tassels were within 20 cm of the ground. Care was taken to avoid breaking corn stalks, which was achieved by applying slow and steady force. Plants throughout plots receiving root lodging were treated the same, and all plots were root lodged the same direction (i.e., simulating predominant westerly wind). To avoid lodged plots interfering with nonlodged plots, all subplots were surrounded by a 3.1-m alley.

2.3 | Data collection

On a whole-plot basis, upper stem (above the ear shoot) recovery from lodging was determined 1 and 2 d after artificially created root lodging using a protractor on three representative plants per plot. This recovery angle utilized a range of 0° to 90°, with 0° indicating a fully erect upper stem and 90° indicating a fully lodged upper stem parallel with the soil surface. At the time of harvest (R3 growth stage), marketable ears, measuring ≥4.5 cm in diameter were hand-harvested from the center two rows of each subplot. Marketable ear number and ear mass were recorded. Ears were husked with an industry-grade husking bed (A&K Development). All husked ears were weighed, and then fresh kernels were cut from the cob with an industry-grade corn cutter (A&K Development) and cob mass was recorded. Kernel mass was calculated as the difference between husked ear mass and cob mass, then adjusted to 76% kernel moisture based on the difference between fresh kernel mass and oven-dried kernel mass.

2.4 | Data analysis

Regression analyses were used to quantify relationships between plant density and sweet corn response. Recovery angle was fitted to linear models as a function of observed plant density using least-squares regression. Regression parameter estimates were used to characterize crop response to plant density. Kernel mass was fitted to quadratic models as a function of observed plant density using least squares regression for both lodged and nonlodged plots. Nonoverlapping 95% confidence intervals were the basis for determining significance of lodging on recovery angle over time and kernel mass. Regression analyses were performed using the *lm()* function in RStudio (R Core Team, 2019).

2.5 | Natural root lodging events

Natural root lodging did not occur in the artificially created root lodging experiment described above. However, natural lodging events did occur in separate studies investigating other aspects of sweet corn response to plant density, including a large collection of on-farm trials throughout the midwestern United States. Although crop growth and yield responses addressing the appropriate objectives from those experiments have been published (Dhaliwal & Williams, 2019; Williams, 2018), unpublished data on root lodging severity was used here to complement the artificially created root lodging experiment. Clearly, we had no control over when or where natural lodging events occurred; available data on the crop and environment associated with the time of root lodging are provided below.

2.6 | Varied environments

Plant density experiments using hybrid DMC 21-84 were conducted in growers' fields throughout Illinois, Minnesota, and

Wisconsin from 2013 to 2017 (Dhaliwal & Williams, 2019). Each experiment was arranged as a randomized complete block design with two replicates. Treatments consisted of 10 target plant densities ranging from 4.2 to 10.9 plants m^{-2}. At a minimum, plot size was four rows wide on 76-cm spacing and 9.1 m in length. All aspects of crop production were managed by growers using their standard cultural practices. Natural lodging events occurred in 6 of the 30 fields, indicative of the sporadic nature of root lodging. For each field where lodging occurred (observed at the time of harvest), rainfall and wind speed data from the closest weather station were used to predict when root lodging likely occurred (Table 1). Taking into account the percentage of plants affected and extent to which they were lodged, plots were scored for root lodging on an 11-point scale: no lodging (0), slight (1–3), moderate (4–6), severe (7–9), and complete (10).

2.7 | Varied hybrids

Ten commercial shrunken-2 sweet corn processing hybrids were grown in a split plot arrangement within a randomized complete block design with four replications in 2015 and 2016 at the University of Illinois Vegetable Crop Research Farm near Urbana, IL (Williams, 2018). Main plot treatment was hybrid and subplot treatment was one of four plant densities (4.3–8.6 plants m^{-2}). Subplot size was four rows wide on 76-cm spacing and 9.1 m in length. In 2016, a natural lodging event was observed near tasseling. Plots were scored for root lodging severity the following day using methodology described above. In 2017, the experiment was repeated, with the exception that a single plant density (5.7 plants m^{-2}) was used. A natural lodging event was observed near tasseling; therefore, plots were scored for root lodging severity. Rainfall and wind speed data from a weather station within 1 km of the site were used to characterize the weather conditions associated with root lodging (Table 1).

2.8 | Data analysis

A quadratic function describes sweet corn yield or profitability response to plant density. The peak of the function occurs at the economic optimum plant density, where profit is maximized. Densities below the economic optimum fail to take advantage of available resources (e.g., light, water, nutrients), and densities exceeding the economic optimum cause yield losses due to excessive intraspecific competition and/or economic losses due to unnecessary seed costs, processing inefficiencies, and so on. Economic optimum plant densities were calculated for varied environments (described in Dhaliwal & Williams, 2019) and varied hybrids (described in Williams, 2018). In addition, the current plant densities used by growers of these hybrids were obtained as described by Dhaliwal and Williams (2019) and Williams (2018). The second objective of the present research was to quantify the extent to which increasing plant density of sweet corn from current to economic optimum densities increases root lodging incidence in natural lodging events. This was tested by first modeling plant density effects on lodging score using least-squares regression for each environment or hybrid. The functional relationships were used to calculate lodging severity at both current and economic optimum plant densities within environment or hybrid. Nonoverlapping 95% confidence intervals were the basis for determining significance of economic optimum plant density on lodging severity. For testing the hybrid effect on root lodging score at a single plant density, one-way ANOVA was performed using glm procedure in SAS (version 9.4, SAS Institute). Separation of hybrid means was determined by Bonferroni-corrected multiple comparisons at $P < .05$.

3 | RESULTS

3.1 | Root lodging influence on recovery angle and yield response to plant density (artificial trial)

Sweet corn recovery from root lodging was influenced more by year and days after lodging than by plant density. After lodging, plants attained a more upright position at lower plant densities; ranging from ∼1 to 3 degrees from vertical per plant m^{-2} (Figure 1a). However, year and days after lodging had a greater effect on the plant's ability to recover from root lodging. Recovery angle 1 d after lodging in 2016 was >55 degrees, whereas recovery angle 1 d after lodging in 2017 was <25 degrees (Figure 1a). By 2 d after lodging, recovery angle improved an additional 10–25 degrees.

Across all conditions, the upper stem of most plants recovered to a near vertical position within a few additional days. Such rapid recovery appeared to overcome any potential interference of root lodging on pollen shed, silk emergence, and floral fertilization.

Yield response to plant density followed a quadratic function. Kernel mass improved with plant density until reaching an asymptote, then declined with additional plant density (Figure 1b). Kernel mass was optimized at 8.1–9.6 plants m^{-2}, depending on the year and occurrence of root lodging event. Although kernel mass in root lodged plots was numerically lower than nonlodged plots, yield response was similar between treatments as evidenced by 95% confidence intervals.

TABLE 1 Weather conditions implicated in natural root lodging events in field experiments of sweet corn in the United States

Experiment type	Field	Cultivar(s)	Year	Estimated date of lodging event[a]	48-h rainfall prior to estimate date of event	Max. mean wind speed preceding estimated date of event	Date of lodging score	Harvest date
					mm	m s^{-1}		
Varied environments	1	DMC 21-84	2016	22 June	36.8	9.4	25 June	1 Aug.
	2	DMC 21-84	2016	19 July	10.7	17.0	22 Jul.	22 July
	3	DMC 21-84	2016	11 Aug.	70.4	11.2	31 Aug.	31 Aug.
	4	DMC 21-84	2017	14 June	22.9	13.0	18 June	7 Aug.
	5	DMC 21-84	2017	27 Aug.	41.1	10.7	7 Sept.	7 Sept.
	6	DMC 21-84	2017	27 Aug.	41.1	10.7	7 Sept.	7 Sept.
Varied hybrids	7	1760MRW, 378A, 7401W, CSHWP9-371, Devotion, Glacial, Heavenly, SV1580SC, WSS3681, XTH3174	2016	6 July	11.7	13.0	6 July	2 Aug.–5 Aug.
	8	1760MRW, 378A, 7401W, CSHWP9-371, Devotion, Glacial, Heavenly, SV1580SC, WSS3681, XTH3174	2017	11 July	35.6	22.0	11 July	3 Aug.–9 Aug

[a] Estimated date in varied environments based on rainfall prior to lodging event and wind speed near the time of the lodging event.

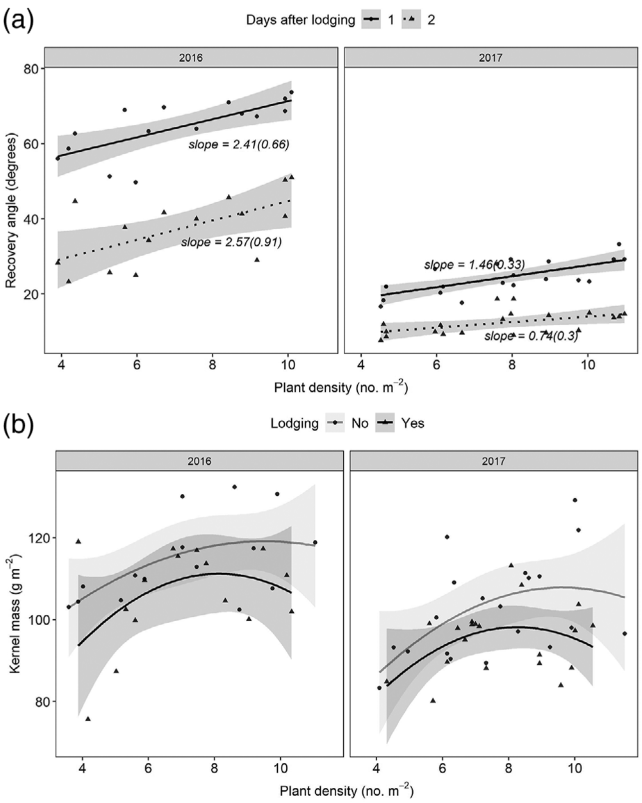

FIGURE 1 Effect of plant density and root lodging on (a) recovery angle measured at 1 and 2 d after the lodging event and (b) moisture corrected kernel mass for sweet corn hybrid DMC 21-84 in 2016 and 2017 in artificially created root lodging experiments near Urbana, IL. Recovery angle was measured at a range of 0° to 90° with 0° indicating a fully erect upper stem and 90° indicating a fully lodged upper stem parallel with the soil surface. Ninety-five percent confidence intervals and slope coefficients, with standard errors in parentheses, are reported

3.2 | Root lodging severity in natural lodging events

Evidence of sweet corn root lodging was observed in only 6 of the 30 growers' fields used to quantify plant density response of a crowding stress tolerant hybrid. Lodging events were characterized by a relatively large amount of rainfall within a 48-h period prior to the estimated date of the event (up to 70.4 mm) and strong winds near the estimated date of the event (up to 17.0 m s^{-1}, Table 1). Root lodging events often occurred after tasseling; however, two fields were believed to be subject to lodging events when the crop was in a vegetative growth stage (i.e., Fields 1 and 4).

Relationships between plant density and lodging score varied greatly by field. For instance, only a weak relationship to plant density was observed in Field 4, and there was no effect of plant density in Fields 2 and 3 (Figure 2). Stronger relationships were observed in Fields 1, 5, and 6. In these three fields, one additional plant per square meter (i.e., 10,000 plants ha^{-1}) increased lodging score by up to one unit (i.e., ∼9%; Figure 2). Across fields, there appeared to be no obvious relationships between lodging score and when the root lodging event occurred.

TABLE 2 Average root lodging score of 10 hybrids, grown at 5.7 plants m^{-2}, in 2016 and 2017 near Urbana, IL, following a natural root lodging event

Hybrid	Lodging score
	0–11[a]
Glacial	4.8 a
7401W	4.0 ab
XTH3174	3.8 ab
CSHWP9-371	3.6 abc
Heavenly	3.2 abc
SV1580SC	2.6 abc
1760MRW	1.8 abc
WSS3681	1.5 bc
Devotion	1.1 bc
378A	0.7 c

Note. Mean separation was determined by Bonferroni-corrected multiple comparisons at $P < .05$.

[a] Root lodging was scored on an 11-point scale: no lodging (0), slight (1–3), moderate (4–6), severe (7–9), and complete (10).

Natural root lodging events also occurred in field experiments with multiple hybrids. Weather conditions associated with root lodging were like those observed in growers' fields described above, with wet and windy conditions (Table 1). Root lodging events occurred 3 to 4 wk prior to harvest, near tasseling.

Hybrids differed greatly in response to conditions favorable for root lodging. Some hybrids were largely tolerant to such conditions, including '378A' and 'Devotion' (Figure 3). In other hybrids, response to root lodging was density-dependent, such as hybrids '7401W' and 'CSHWP9-371' (Figure 4). Hybrid response at a single plant density confirmed wide variation in hybrid tolerance to conditions associated with root lodging (Table 2).

Across all hybrids and environments, the current plant density used by growers ranged from 5.5 to 6.9 plants m^{-2} (Table 3). Based on empirical research in growers' fields, the economic optimum plant density ranged from 6.1 to 8.7 plants m^{-2}. The small to nonexistent difference in lodging scores between these two densities was not statistically different for any field or hybrid (Table 3).

4 | DISCUSSION

The degree to which lodged sweet corn plants recovered to a vertical position was driven far more by the environment than plant density. Most plants recovered to a near vertical

TABLE 3 Significance of current vs. economic optimum plant density on root lodging caused by natural root lodging events in sweet corn in the United States

Experiment type	Field	Cultivar	Current plant density	Lodging at current plant density	Economic optimum plant density	Lodging at economic optimum plant density	Difference in lodging	Significance
			no. m^{-2}	0–11	no. m^{-2}	0–11		
Varied environments	1	DMC 21-84	5.8[a]	1.8	7.4[a]	2.9	1.1	NS[c]
	2	DMC 21-84	6.9[a]	4.8	8.7[a]	5.3	0.4	NS
	3	DMC 21-84	5.5[a]	4.4	6.1[a]	4.4	0.0	NS
	4	DMC 21-84	5.8[a]	1.6	7.8[a]	2.0	0.4	NS
	5	DMC 21-84	5.6[a]	6.2	6.5[a]	6.9	0.7	NS
	6	DMC 21-84	5.6[a]	3.9	6.1[a]	4.4	0.5	NS
Varied hybrids	7	1760MRW	5.5[b]	0.8	6.1[b]	1.1	0.3	NS
	7	378A	5.5[b]	0.5	6.1[b]	0.7	0.2	NS
	7	7401W	5.5[b]	4.8	6.1[b]	5.4	0.6	NS
	7	CSHWP9-371	5.5[b]	3.7	6.1[b]	4.6	0.9	NS
	7	Devotion	5.5[b]	0.2	6.1[b]	0.3	0.1	NS
	7	Glacial	5.5[b]	2.5	6.1[b]	3.0	0.5	NS
	7	Heavenly	5.5[b]	3.5	6.1[b]	4.2	0.7	NS
	7	SV1580SC	5.5[b]	2.9	6.1[b]	3.7	0.8	NS
	7	WSS3681	5.5[b]	2.1	6.1[b]	2.5	0.4	NS
	7	XTH3174	5.5[b]	5.1	6.1[b]	5.5	0.4	NS

Note. Root lodging was scored on an 11-point scale: no lodging (0), slight (1–3), moderate (4–6), severe (7–9), and complete (10). Nonoverlapping 95% confidence intervals were the basis for identifying differences in lodging scores between current and economic optimum plant densities.

[a] From Dhaliwal & Williams, 2019. Economic optimum plant densities varied with environment.

[b] From Williams, 2018. All hybrids had a common response to plant density.

[c] NS, nonsignificant.

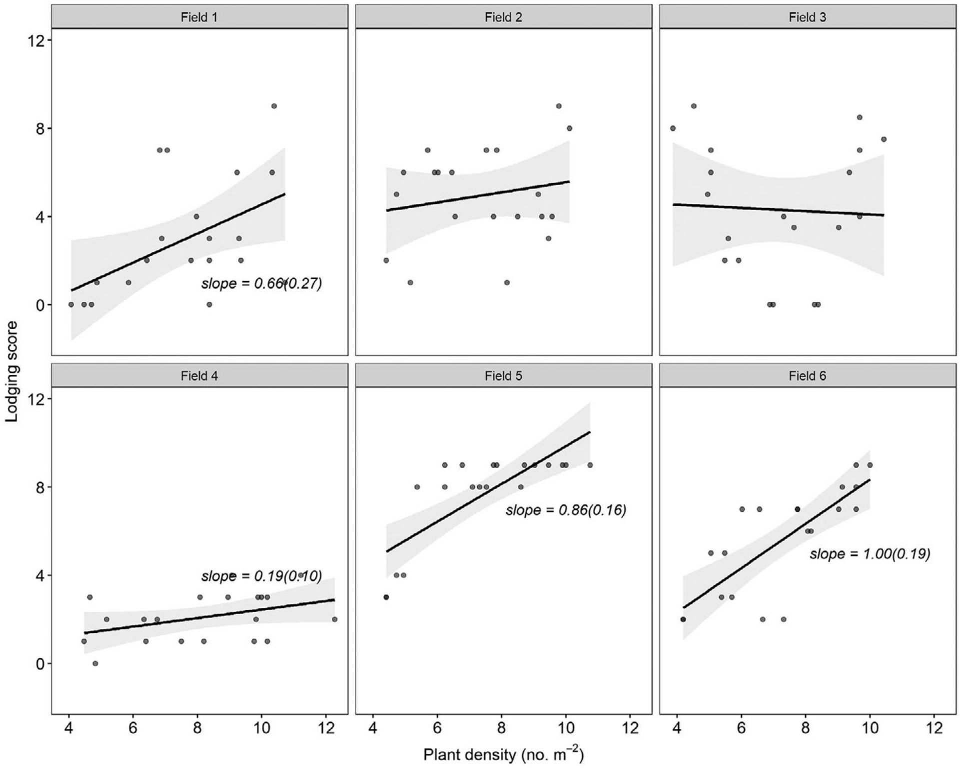

FIGURE 2 Relationship between plant density and lodging score for DMC 21-84 across six fields in the United States following natural root lodging events. Root lodging was scored on an 11-point scale: no lodging (0), slight (1–3), moderate (4–6), severe (7–9), and complete (10). Plant density effects on lodging score are described with linear models. Ninety-five percent confidence intervals and slope coefficients, with standard errors in parentheses, are reported

position within a few days, similar to findings of Carter and Hudelson (1988). The growth stage also has a major influence on corn's ability to recover from root lodging (Nielsen, 2002). Early growth stages (e.g., ≤V5) may fully recover, whereas later stages often have a pronounced curvature in the lower stalk, called goose-necking.

Root lodging decreases grain yield in field corn, the extent to which is driven largely by timing of the lodging event (Carter & Hudelson, 1988; Nielsen, 2002). The response of root lodging to plant density was not affected by field corn hybrid or row width (van Roekel & Coulter, 2012). In the present work on sweet corn, where plants were artificially root lodged at VT, there was no statistical difference in sweet corn yield between lodged and nonlodged plots. Apparently root lodging did not interfere with pollen shed or silk emergence, likely because the upper stem of plants returned to a near-vertical position within a few days. Sweet corn also has particularly large tassels. Nonetheless, root lodging can slow sweet corn harvest operations, and yield is compromised the most when the lodging event occurs just days before harvest (R3 growth stage) because plants have neither the time nor phototrophic ability to recover (C. Bahr, personal communication, 2013).

Root lodging occurred in only 20% of growers' fields used to quantify plant density response of a crowding stress tolerant hybrid, reflecting the erratic nature of climate conditions inducing root lodging (Fouéré et al., 1995; Gardiner et al., 2016). Primary weather factors (i.e., storms) involved in root lodging include rain, sufficient to compromise the root–soil anchorage system, and wind loading on the corn canopy, from horizontal to downdraft (Brune et al., 2017). Storms during the growing season not only vary in intensity but are unevenly distributed within a field and over years, so that lodging can be highly variable.

Commercial sweet corn hybrids differ greatly in their response to conditions favoring root lodging. Although Tracy (1990) showed exotic maize populations varied in root lodging susceptibility, the primary literature lacks previous reports of the effect of plant density on sweet corn root lodging. In the present research, specific commercial cultivars were tolerant to root lodging conditions, regardless of environment or plant density. A molecular basis of root lodging traits has received some study in field corn (Bruce et al., 2001; Farkhari et al., 2013); the extent to which such results apply to sweet corn is unknown.

Across 16 experimental comparisons of sweet corn response to plant density where natural root lodging was observed, which comprised seven environments and 11 commercial hybrids, there was no difference in root lodging between current and economic optimum plant densities. The

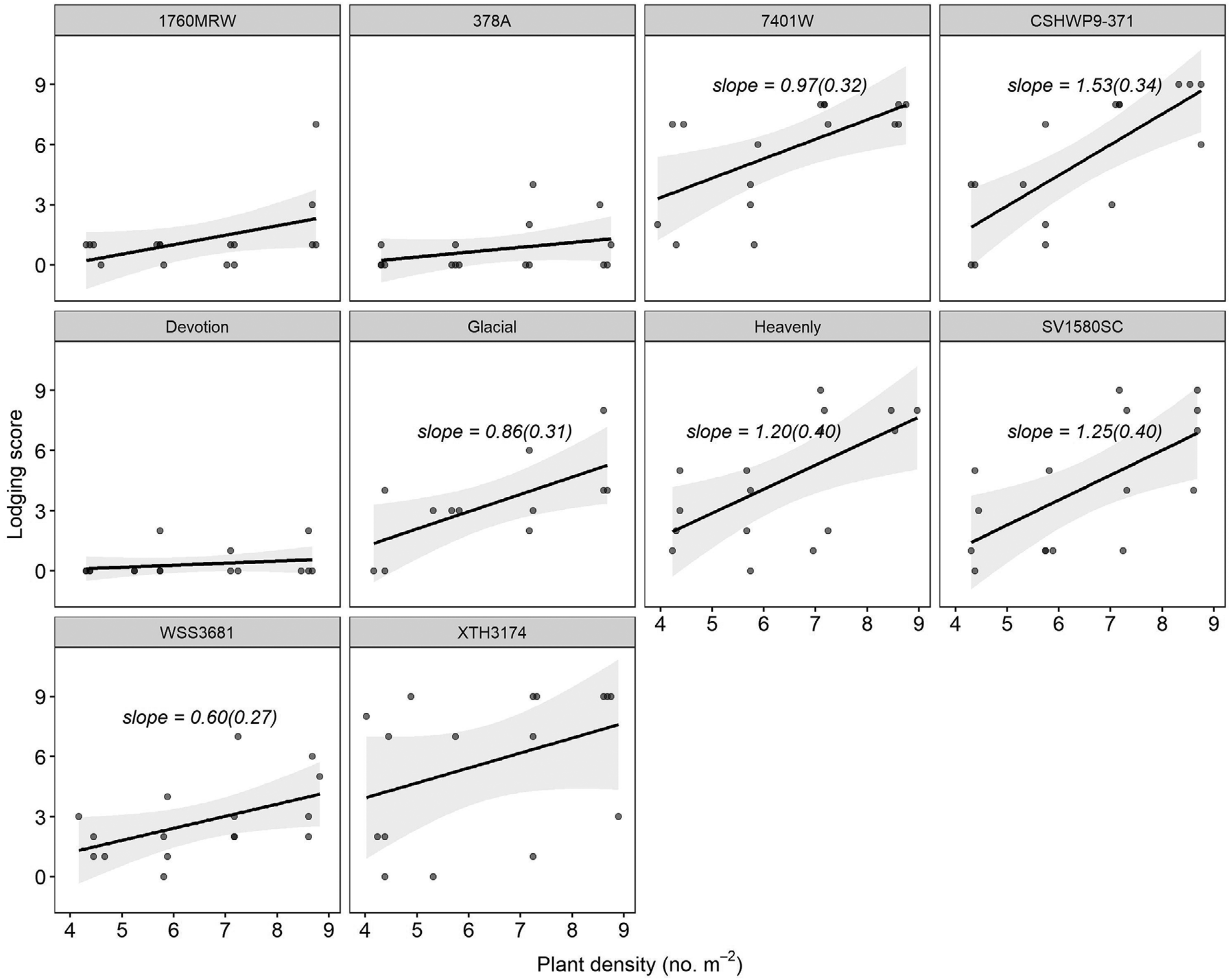

FIGURE 3 Relationship between plant density and lodging score for 10 sweet corn hybrids grown in 2016 near Urbana, IL following a natural root lodging event. Root lodging was scored on an 11-point scale: no lodging (0), slight (1–3), moderate (4–6), severe (7–9), and complete (10). Plant density effects on lodging score are described with linear models. Ninety-five percent confidence intervals and slope coefficients, with standard errors in parentheses, are reported

single largest comparison (which was nonsignificant) in root lodging score (on an 11-point scale) between current and economic optimum plant densities was 1.1 units, whereas the mean comparison across all studies was only 0.5 units. Statistically, there is no greater risk of root lodging in sweet corn by increasing plant density from current to economically optimized levels. Agronomically, hybrid and environment are much larger drivers of root lodging in commercial sweet corn. Crop genetics and environmental factors are major drivers of root lodging in field corn (Brune et al., 2017; Farkhari et al., 2013; Liu et al., 2012; Stamp & Kiel, 1992).

5 | CONCLUSIONS

Exploitation of plant density tolerance in sweet corn, including the use of density-tolerant germplasm at economic optimum plant densities, has the potential to improve crop yield and profitability. However, does increasing plant densities for this purpose also increases incidence of root lodging? We examined this concern with multiple experimental approaches, including artificially created root lodging events in field trials and natural lodging events in growers' fields throughout the U.S. Midwest.

Although root lodging can interfere with sweet corn harvest operations and cause serious yield losses, optimizing plant density for profitability has no influence on the severity of root lodging. This work shows factors other than plant density dominate sweet corn's potential for, and recovery from, root lodging. The crop's growth response to the environment is a major factor in the development of the root–soil anchorage system. The severity of the weather event and when it occurs relative to crop development dictate the impact on crop yield. Also, commercial sweet corn hybrids differ greatly in their susceptibility to root lodging. Additional research on the morphological and physiological basis for differential susceptibility to root lodging would facilitate additional development of root-lodging resistant sweet corn cultivars.

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AUTHOR CONTRIBUTIONS

Martin Williams, II: Conceptualization; Investigation; Methodology; Project administration; Resources; Supervision; Writing-original draft. Nicholas Hausman: Data curation; Investigation. Daljeet Dhaliwal: Formal analysis; Investigation; Visualization. Tony Grift: Writing-review & editing. Martin Bohn: Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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