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Abnormal ear development in corn: Does hybrid, environment, and seeding rate matter?

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Abstract

Corn (*Zea mays* L.) yields have increased in the United States since the 1930s and in other parts of the world since the 1950s and 1960s because of improvements in agricultural management and genotypes. Despite these increases, production concerns still exist. In July 2016, abnormal ear development (multi-ears per node, barbell-ears, and short-husks) was reported in cornfields that extended from the Texas Panhandle to eastern Colorado and east through Kansas, Nebraska, Iowa, and Illinois. Surveys in Nebraska farmer fields revealed significant productivity losses due to the issues, but little was known about the underlying causes. A research study was conducted in four Nebraska fields during the 2018 and 2019 growing seasons. The research investigated the effects of hybrids, environments, seeding rates, and their interactions on abnormal ears. Eight hybrids, eight environments, and five seeding rates were studied. About 63,500 plants were individually assessed at or after the dent stage (R5). Grain yield ranged from 4.3 to 20.1 Mg ha^{-1}. In 2018, about 5% of ears were abnormal; in 2019, about 11%, if combined, about 8%. Higher-yielding hybrids were associated with lower percentages of abnormalities. Hybrids, environments, and seeding rates influenced the occurrence of abnormal ears. In most cases, abnormal ears had lower heights in the canopy, suggesting that primary ear loss may be a factor. The results reinforced the overriding hypothesis that ear abnormalities result from environmental, genetic, and management interactions. Depending on the environment, selecting certain hybrids with optimum seeding rates could help mitigate the occurrence of abnormal ears.

1 | INTRODUCTION

Corn (*Zea mays* L.) is one of the major cereal crops (Lobell et al., 2008) and plays a fundamental role on global scales: food, feed, fiber, and fuel. Corn yields have consistently increased since the 1930s in the United States (US) and worldwide since the 1950s due to improvements in agricultural management and genotypes (Duvick, 2005; Li et al., 2011; Long et al., 2006; Ma et al., 2014; Mueller et al., 2019). More recently, yield gains have also been associated with climate in favorable environments (Rizzo et al., 2022). These latter authors studied the contributions of factors driving yield gain from 2005 to 2018; their results proposed that yield gains

Abbreviations: BB1, barbell-ear 1; BB2, barbell-ear 2; BB3, barbell-ear 3; SH, short-husk.

were 48% due to climate trends, 39% due to improvements in agronomics, and the remainder 13% due to improvements in genetic yield potential.

Previously, Ray et al. (2015) documented that climate accounts for about one-third of the observed variations in yield. Weather (e.g., short-term atmospheric conditions) and climate (e.g., long-term conditions) are two key drivers that influence changes in agricultural production (Kukal & Irmak, 2018). Significant changes in these variables can suppress or enhance the advantages of technological advances or improved management. Temperature and precipitation are the most studied variables regarding weather/climate and crop relationships (Kukal & Irmak, 2018; Leng & Hall, 2020; Ray et al., 2015; Secchi et al., 2021; Simmonds et al., 2013).

Many factors that influence plant growth and development affect corn yield (Abendroth et al., 2011; Below, 2018; Ortez et al., 2022a, 2022b). These factors include weather, nutrients, genetics, previous crop, plant population, pest and disease management, tillage system, planting dates, and growth regulators. As for any crop responses, factors like this continuously interact. The latter refers to the genetic × environment × management (G × E × M) interaction, which ultimately defines crop responses and yields.

Over the years, several abnormal ear development symptoms have been reported (Nielsen, 1999, 2006; Thomison et al., 2015, 2022a), but in recent years, these have become of major concern. In 2016, widespread corn ear abnormalities were reported in Texas, Colorado, Kansas, Nebraska, Iowa, and Illinois (Ortez et al., 2022c). The reports often originated from high-yielding environments (e.g., high input systems); 35% to 91% per plant yield losses were documented for abnormal ears relative to normal ears. The abnormal ear reports raised questions about the suitability and stability of corn hybrids across different environments and management practices.

Several questions remained unanswered at the time, and research was not yet conducted to address these questions. The current research project focused on better understanding G × E × M effects on the three widespread abnormal ear symptoms reported in Nebraska and the region in 2016 (Elmore et al., 2016; Ortez et al., 2022c, 2019). The three symptoms are multiple ears per node (herein termed multi-ears), barbell-ears, and short-husks (Figure 1; Ortez et al., 2022a).

Multi-ears are also known as "bouquet ears"; more than one ear develops at the upper-most ear node on a single ear shank (Figure 1a–c). Anywhere from two (Figure 1a,b), four (Figure 1c), and up to eight ears have been observed on the same plant node. The expected development timing for this group is after ear initiation (V4 to V6) and before pollination (VT or R1). All corn growth and development stages discussed here are based on Abendroth et al. (2011).

Barbell-ears: Kernels on barbell ears may only form at the tip or the base of the ear or both locations, with missing kernels on the middle section (Figure 1d–f). In addition to the missing kernels, a significant decrease in the cob diameter occurs in the damaged area, suggesting severe stress that affected kernel development and the cob. Depending on the barbell type (how far the ear was developed when the potential stressor(s) occurred), the expected timing of development is during ear size determination, V6 to V12, and up to R1.

Short-husk ears have shortened husks that leave the cob and kernels protruding beyond the husks. The ears of some hybrids often protrude a bit beyond the husk leaves; however, the symptoms under study are more severe, with as low as just 10% to 30% of husk cover (Figure 1g–i). The expected development timing for this group is during the late vegetative stages and close to tasseling and pollination, V18 to R1.

Given this background and the need for a better understanding of abnormal ears, we established eight site-year combinations of field experiments in Nebraska to (1) study the effect of hybrids, environments, and seeding rates on abnormal ears; (2) determine the distribution of abnormal ears among different ear types; and (3) compare normal versus abnormal ear placement characteristics. The results will help shape the understanding of potential factors responsible for abnormal ear development in corn and to be better prepared for the likelihood of future abnormal ear events.

Core Ideas

- Widespread abnormal ears and productivity losses occurred in cornfields in 2016, and new research was needed.
- Higher-yielding hybrids were associated with lower percentages of abnormal ears.
- Abnormal ears were placed lower on stalks, suggesting that primary ear loss may be a factor.
- Interactions among hybrids, environments, and seeding rates affected the development of abnormal ears.

2 | MATERIALS AND METHODS

2.1 | Experimental sites

Field experiments were conducted in four South Central and Eastern Nebraska fields during the 2018 and 2019 growing seasons, making up eight distinct environments (Table 1). The locations were near Filley, Hooper, Lawrence, and York in Nebraska (corresponding to Gage, Dodge, Nuckolls, and York counties, respectively). All four studies were located in on-farm locations in both years. In 2018, planting dates ranged from May 4 to May 10. In 2019, fields were planted between

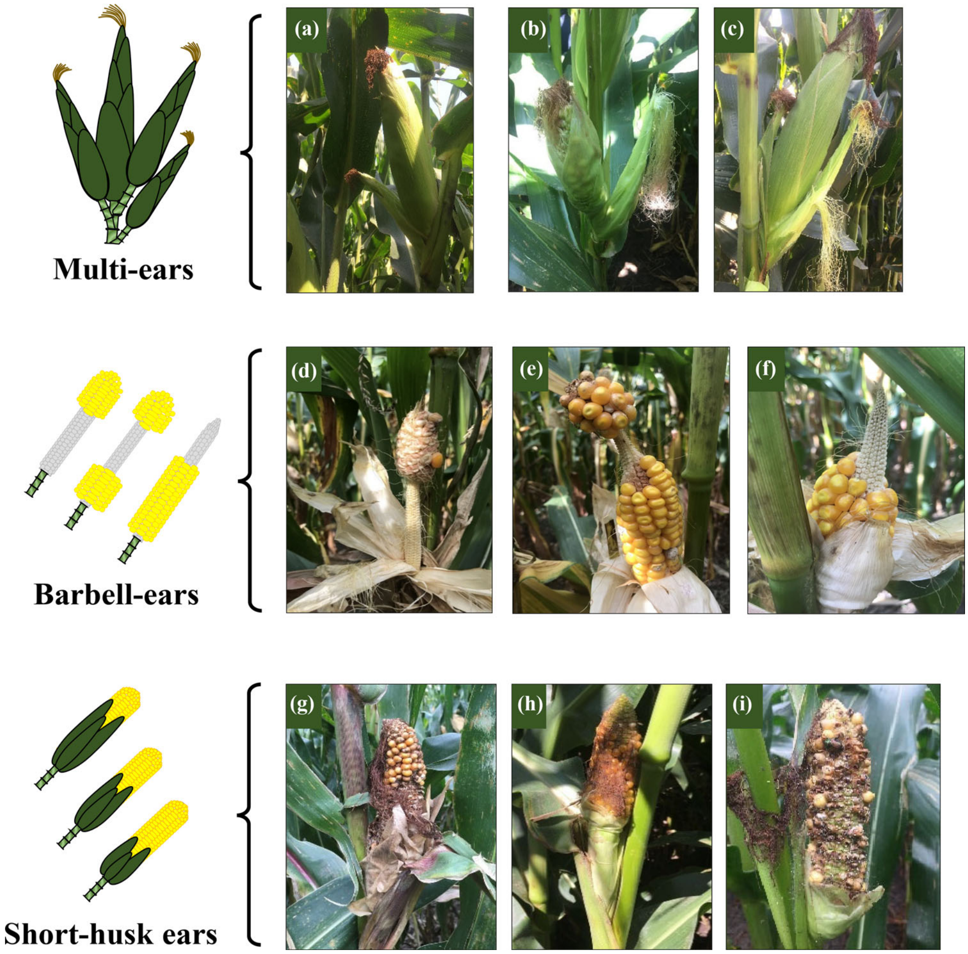

FIGURE 1 Multi-ears—more than one ear on the same plant node (a–c). Two ears (a,b) and four ears (c). Barbell-ears—kernels missing in sections of ears (d–f) with significant cob diameter decreases. Barbell-ear 1: kernels missing at the base of the ear (d). Barbell-ear 2: kernels missing at the middle (e). Barbell-ear 3: kernels missing at the tip (f). Short-husk ears—kernels not fully covered by husks, thus, are exposed (g–i). About 30% of husk cover (g), about 20% of husk cover (h), and about 10% of husk cover (i). *Source*: Graphics: Justin McMechan. Images: Osler Ortez.

May 15 and May 20, later than in 2018, due to wet conditions. Two fields were pivot irrigated, and two were rainfed each year; the previous crops were either soybean or wheat; the soil types included Wymore, Moody, Crete, and Hastings series (silty clay loam and silt loam textures; 0–1% and 0–2% slopes). These characteristics provided different environments, allowing this study to cover a comprehensive range of conditions. All plots were 6.09 m long and 3.04 m wide, consisting of four rows spaced at 76.2 cm.

2.2 | Treatment and experimental design

The experiment was arranged as a split-plot in a Randomized Complete Block Design (RCBD). Treatments were five seeding rates and eight hybrids. Seeding rates were the main-plot treatment, and hybrids were the split-plot treatment. Each treatment was replicated three times in each environment (i.e., site-year combinations).

The five seeding rates were 44,000, 64,000, 84,000, 104,000, and 124,000 seeds ha^{-1}. The eight hybrids were P0157, P0339, P0801, P0801 (seed source 2016), P0832, P1311, P1311 (seed source 2016), and P1370; from those, five were considered "susceptible," and three were "checks" (Table 2). On the practitioner side (e.g., farmers, seed industry), the susceptible hybrids were often considered "racehorse" materials, and the check hybrids were often considered "workhorse" materials. The eight hybrids were commercially available from DuPont Pioneer. Five susceptible hybrids were selected based on (1) recommendations from farmers and seed company agronomists and (2) the hybrid's frequency of ear abnormalities from field observations in farmer fields during 2016 (Ortez et al., 2022c). Three check hybrids were added to the study based on their genetic background, proximity in relative maturity to susceptible hybrids, and the absence of reports of abnormal ears. The 2016 seed sources (P0801 and P1311) were selected further to investigate differences between these hybrids with differing

TABLE 1 Summary of study locations, planting dates, water regimes, previous crop, and soil types in four South Central and Eastern Nebraska fields in the 2018 and 2019 growing seasons.

Location	County	Year	Latitude	Longitude	Planting date (D/M/YY)	Water regime	Previous crop	Soil types
Filley	Gage	2018	40.3201	−96.6208	6/5/2018	Rainfed	Soybean	Wymore series Silty clay loam 0% to 2% slopes
Hooper	Dodge	2018	41.6470	−96.5703	10/5/2018	Pivot irrigated	Soybean	Moody series Silty clay loam 0% to 2% slopes
Lawrence	Nuckolls	2018	40.2781	−98.1999	4/5/2018	Rainfed	Wheat	Crete series Silt loam 0% to 1% slopes
York	York	2018	40.8185	−97.6353	4/5/2018	Pivot irrigated	Soybean	Hastings series Silt loam 0% to 1% slopes
Filley	Gage	2019	40.3200	−96.6263	15/5/2019	Rainfed	Soybean	Wymore series Silty clay loam 0% to 2% slopes
Hooper	Dodge	2019	41.6470	−96.5768	20/5/2019	Pivot irrigated	Soybean	Moody series Silty clay loam 0% to 2% slopes
Lawrence	Nuckolls	2019	40.2780	−98.2016	16/5/2019	Rainfed	Wheat	Crete series Silt loam 0% to 1% slopes
York	York	2019	40.8140	−97.6230	15/5/2019	Pivot irrigated	Soybean	Hastings series Silt loam 0% to 1% slopes

TABLE 2 The information on hybrids utilized in the study is included: Hybrid, seed source, commercial name, company, relative maturity, and its classification based on 2016 field observations for whether susceptible or check in terms of ear abnormalities presence.

Hybrid	Seed source	Commercial name	Brand	Relative maturity[a]	Classification[b]
P0157	2018	P0157AMXT	DuPont Pioneer	101	Susceptible
P0339	2018	P0339AMT	DuPont Pioneer	103	Check
P0801	2018	P0801AMXT	DuPont Pioneer	108	Susceptible
P0801	2016	P0801AMXT	DuPont Pioneer	108	Susceptible
P0832	2018	P0832AMX	DuPont Pioneer	108	Check
P1311	2018	P1311AMXT	DuPont Pioneer	113	Susceptible
P1311	2016	P1311AMXT	DuPont Pioneer	113	Susceptible
P1370	2018	P1370 AMXT	DuPont Pioneer	113	Check

[a]Relative maturity is expressed in the number of days reflected in each hybrid's comparative relative maturity (CRM) label.
[b]The classification is given in reference to (1) recommendations from farmers and seed company agronomists and (2) hybrid frequency of ear abnormalities from field observations in farmer fields during 2016 reports. The "check" hybrids were expected to have few or no abnormalities. The "susceptible" hybrids were expected to have high frequencies of abnormalities.

seed production years or seed lot numbers. Based on field observations of 2016, these two hybrids were thought to be two of the most susceptible, perhaps due to their widespread adoption in the region. All other seed was sourced from season 2018. Refuge seeds were screened out in all eight hybrids using a color sorting machine before planting each year.

2.3 | Crop measurements

2.3.1 | Stand counts

Counts of emerged plants were made at the V6 stage (six collared leaves) to determine final stands. Counts were gathered from the entire length of the two center rows of each plot. The counts were utilized to estimate the percentages of abnormal ears per plot based on the count of plants with abnormal ears relative to the total count of plants per plot. Additionally, stand counts helped to confirm that seeding rate treatments were adequately established in the study.

2.3.2 | Ear classification

Ear classification was gathered by assessing the primary ear (uppermost ear) on every plant in the two center rows of all plots, at or after the R5 stage (dented stage), in a nondestructive way to avoid compromising the ear's productivity.

About 63,500 plants were individually assessed and classified (normal or abnormal) over the two growing seasons (2018 and 2019) in the four fields. All ears were classified during the in-field assessments:

For the multi-ear group, the number of ears present on the upper-most ear node was counted on each plant if more than one ear was present, and these were grouped in the multi-ear category (Figure 1a–c).

For barbell-ears, depending on where the kernels were missing, three subgroups were developed to help classify barbell-ears: missing kernels at the base (BB1, Figure 1d), missing kernels at the middle (BB2, Figure 1e), and missing kernels at the tip (BB3, Figure 1f).

Next, a visual estimation was made for the short-husks with a percentage of husk cover in the affected ears (Figure 1g–i). Within this ear type, the ears were categorized into three groups: short-husk 30 (SH30), short-husk 50 (SH50), and short-husk 70 (SH70)—larger numbers equate to longer husks and, thus, more ear coverage. If the resulting husk cover was less than 40%, ears were categorized as SH30. If the husk cover was between 40% and 60%, the assigned category was SH50. If the husks cover was more than 60% and less than 80%, the assigned category was SH70. Ears with husk cover greater than 80% were not considered abnormal to avoid misclassifying hybrids with a small degree of husk shortage.

In a few instances, two classifications could occur for a given ear, wherein the earlier-occurring symptom would denote that ear (i.e., earlier occurrence: multi-ear > barbell-ear > short-husk). This situation happened in up to 4.9% of ears in a given site-year, but overall (across site-years), only 1.7% of ears had more than one classification noted. The two situations observed were (1) multi-ears, having short-husk for at least one of the ears, and (2) barbell-ears showing short-husk in the tip. When those situations were observed, those ears were classified either as multi-ear or barbell ears, given their earlier developmental timing (multi-ears and barbell-ears develop earlier in the season, relative to short-husks).

2.3.3 | Ear heights

For plants with abnormal ears, the height of the ear-bearing node was measured individually and then averaged for each plot. An uppermost ear height was estimated for normal ears in each plot by averaging the ear height of about 10 representative plants. Ear heights were measured from the ground level to the node bearing the uppermost viable ear in the two center rows of each plot when abnormal ears were present.

2.3.4 | Plot yields

Corn yield was collected after the crop reached physiological maturity (R6) by harvesting the two center rows in each plot using a plot combine. Plot yields and moisture were adjusted to megagrams (Mg) per hectare (ha) and reported at 13.5% grain moisture content.

2.4 | Statistical analysis

Grain yield was analyzed using a linear mixed model (LMM) with fixed effects of hybrid, seeding rate, environment, and their interactions. Random effects for replications within environment and seeding rate within replications and environment were included to account for variability due to the block and whole-plot level variance, respectively, with the residual variance accounting for the split-plot unit variance.

A binomial generalized linear mixed model (GLMM) analysis with a cumulative log link function was used to fit the number of abnormal ears out of the total number for abnormal ear percentages. Laplace integral approximation was used for the estimation method due to the extreme proportions of abnormal ears. This analysis was performed to test the fixed effects of hybrid, seeding rate, environment, and interactions. Random effects were included to account for block variability (replications within the environment) and whole-plots (seeding rate within replications and environment). All three ear groups (multi-ears, barbell-ears, and short-husks) were analyzed together, given the predominance of short-husks, the low overall numbers present in the study, and many 0s as a response across the board. Abnormal ear counts on each ear across all conditions are available in Tables S1–S3.

Ear placement for each plot represented the average ear height of the two groups (normal and abnormal ears), except when abnormal ears were not found. A LMM was fit to the average ear height with fixed effects of hybrid, seeding rate, environment, ear type group, and their interactions. Random effects accounted for the variability between blocks, whole plots, and split plots, with the residual variance accounting for the variability within the ear type group. Estimated parameter coefficients were adjusted to be proportional to the observed margins using the BYLEVEL option to account for unbalanced data due to no abnormal ears in certain treatment combinations.

The combination of four locations and two years structured the environment as a categorical variable. All analyses were conducted in SAS 9.4 (SAS Institute) using the glimmix procedure (PROC GLIMMIX). Satterthwaite degrees of freedom adjustment were utilized to control Type I error rates and

TABLE 3 Weather characterization of study locations for temperatures (mean maximum, mean minimum, mean average [Avg.], and historical mean Avg.) and precipitation (season and historical mean), May through October.

		Temperature (°C)				Precipitation (mm)		Growing degree days (GDD, °C)	
Location	Year	Mean maximum	Mean minimum	Mean avg.	Historical mean avg.	Season	Historical mean	Accumulative season	Historical accumulation
Filley	2018	24.8	12.0	18.4	18.6	788	652	1890	1817
Hooper	2018	24.2	12.1	18.2	17.6	685	627	1834	1688
Lawrence	2018	25.3	7.6	17.9	18.2	638	571	1875	1768
York	2018	23.4	11.7	17.6	18.1	620	591	1822	1754
Filley	2019	24.8	12.4	18.6	18.6	847	652	1780	1817
Hooper	2019	24.2	12.1	18.2	17.6	824	627	1721	1688
Lawrence	2019	27.2	13.6	17.8	18.2	611	571	1688	1768
York	2019	22.9	11.7	17.3	18.1	864	591	1703	1754

Note: Additionally, growing degree day accumulation (GDD) for 2018, 2019, and historical in four locations, South Central and Eastern Nebraska, May through October. The historical means represent the 30-year summary between 1981 and 2010 at the different locations, May through October. All-weather information was retrieved from the High Plains Regional Climate Center (HPRCC, https://hprcc.unl.edu/).

account for the random effects in the split-plot experimental design. Residual and qq-plots were used to assess model fit and normality assumptions when appropriate. Tukey LSD is reported at an $\alpha = 0.05$ significance level.

2.5 | Weather information

Weather information was gathered and summarized for all fields from May through October during the 2018 and 2019 growing seasons (Table 3; Figure 2). A historical summary (1981 to 2010) was included for the same period at each location. Additionally, the 2016 weather results were added as they represent the conditions faced when widespread abnormal ears occurred in Nebraska and the region (Ortez et al., 2022c). In-season monthly summaries for June, July, and August were added in all locations. Following planting dates from early to mid-May (Table 1), these are the critical months for ear formation. All-weather information was retrieved from the High Plains Regional Climate Center (HPRCC, https://hprcc.unl.edu/).

3 | RESULTS AND DISCUSSION

3.1 | Weather: Historical and seasonal comparisons

This project's summary of weather results showed the deviations between the 2018 and 2019 seasons in reference to historical records at the four studied locations (Figure 2; Table 3). For the Filley location (Figure 2a), the 2018 and 2019 growing seasons differed from the historical summary with greater precipitation, 136 mm more in 2018 and 195 mm more in 2019 in relation to the average between 1981 and 2010. These results indicated that the Filley location was wetter than usual, while the temperature results were similar to historical values. For Hooper (Figure 2b), 2018 and 2019 had 58 and 197 mm of precipitation above the historical values, while season-long temperatures were slightly warmer (∼0.5°C) than historical values. Lawrence (Figure 2c) had close to normal precipitation (about 600 mm of precipitation for both years) with slightly colder (∼0.2°C) weather. York (Figure 2d) in 2018 had close to normal precipitation, with 620 mm, while 2019 precipitation was considerably wetter, 864 mm. Both years were slightly colder, with a ∼0.4°C temperature decrease in 2018 and a ∼0.8°C decrease in 2019 compared to historical.

Hot temperatures harm crop yields due to increased potential for heat stress, directly and indirectly, due to soil moisture deficits (Leng & Hall, 2020). On the other hand, low precipitation can lead to stomata closing, less carbon uptake, and lower yields altogether (Qaderi et al., 2019). Based on May planting dates (Table 1), June, July, and August are the critical months in terms of the potential for developing abnormal ears. Following planting dates from early-to-mid May, the months of June–July–August would approximately encompass the period of early vegetative stages (V4–V5) up to tassel (VT) and silking (R1). This period matches the expected timing (based on the symptomology and the different processes the plant undergoes) of abnormal ear development proposed by Ortez et al. (2022a), which covers the start of ear formation and up to silking (R1). For the in-season analysis across the studied locations (Figure 2e–h), the 2018 (blue squares) and 2019 (red circles) monthly data for June, July, and August are presented. The three-month period in 2018 tended to have warmer temperatures than in 2019. June and July were the warmest months in 2018 (June–July > August). In 2019, the highest temperatures were achieved in July, followed by August and June.

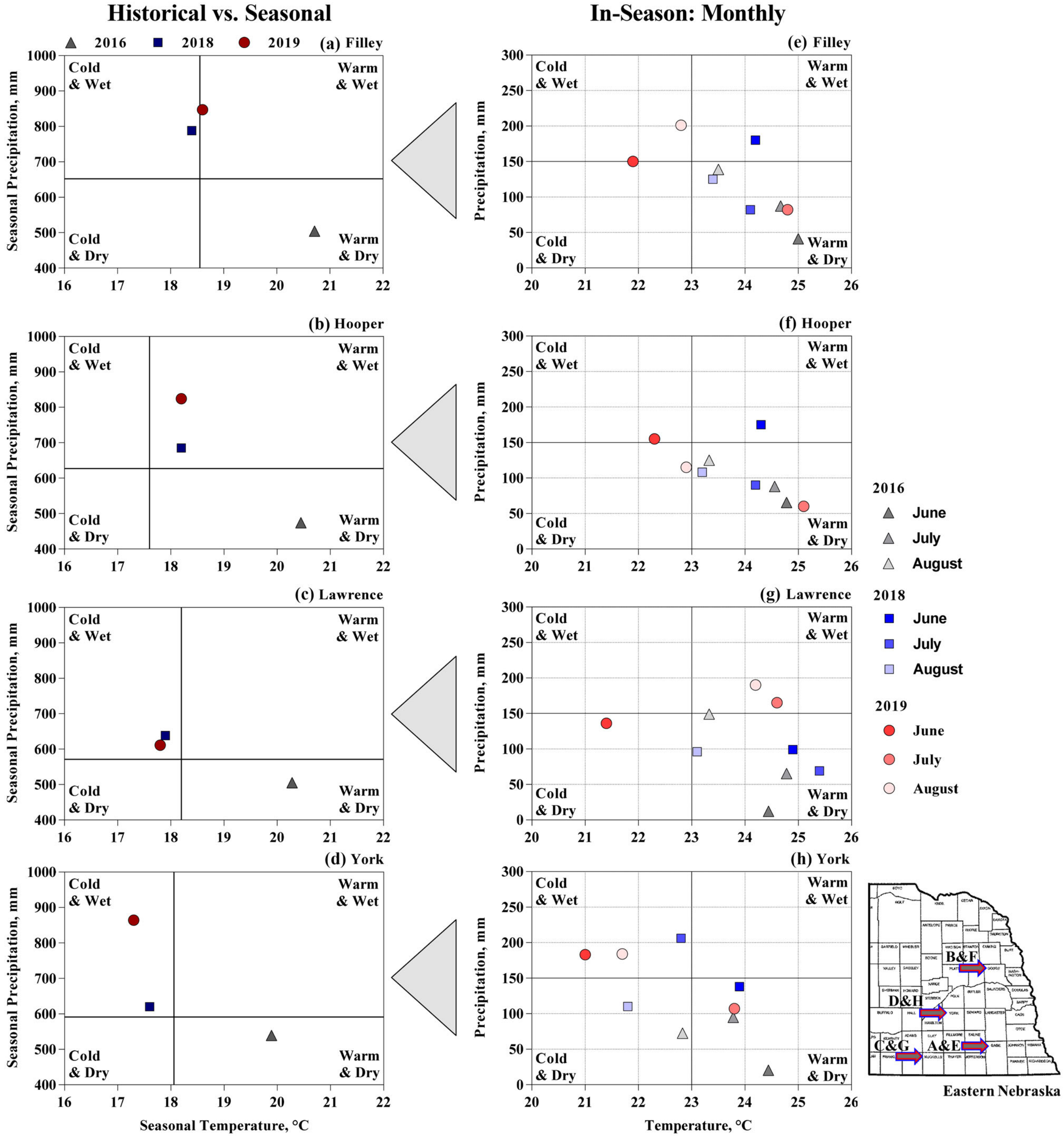

FIGURE 2 Weather characterization (mean temperature in °C and accumulative precipitation in mm) for the historical (solid lines, means from 1981 to 2010 at each site) and growing season (May through October) in the dark gray triangles (2016), dark blue squares (2018), and dark red circles (2019). Filley (a) is located in Gage county, Hooper (b) is located in Dodge county, Lawrence (c) is located in Nuckolls county, and York (d) is located in York county. In-season monthly summaries for June, July, and August on the three lighter gray (2016), three lighter blue (2018), and three lighter red colors (2019) for Filley (e), Hooper (f), Lawrence (g), and York (h) locations.

The 2016 weather characterization is also presented in Figure 2. This summary represents the conditions when widespread abnormal ears were reported from Nebraska and several other states in the United States (Ortez et al., 2022c). From the season-long results (Figure 2a–d), 2016 was a very different year compared to the 2018 and 2019 summaries. All fields in 2016 were warmer and drier. Temperatures in 2016 averaged approximately 2-degree Celsius higher than historical, 2018, and 2019. Additionally, the cumulative season precipitation in 2016 was below 550 mm for all fields. For June–July–August (Figure 2e–h), the same results are confirmed, warmer and drier weather during those three

TABLE 4 Analysis of variance (ANOVA) results (F value, numerator DF, denominator DF, and *p*-value) for grain yield, abnormal ears percentage, and ear heights. The summary includes four fields and two growing seasons (2018 and 2019) in South Central and Eastern Nebraska.

		Grain yield Mg ha^{-1}			Abnormal ears percentage (%)			Ear heights[a] centimeters (cm)		
Label	**Factor tested**	***F*-value**	**DF**	***p*-Value**	***F*-value**	**DF**	***p*-Value**	***F*-value**	**DF**	***p*-Value**
G	Hybrid	29.4	7, 560	**<0.0001**	8.6	7, 560	**<0.0001**	155.9	7, 392	**<0.0001**
E	Environment	57.6	7, 16	**<0.0001**	6.2	7, 16	**0.0012**	16.1	7, 16	**<0.0001**
M	Seeding Rate	34.4	4, 64	**<0.0001**	2.0	4, 64	0.1057	60.7	4, 76	**<0.0001**
G × E	Hybrid × Environment	4.1	49, 560	**<0.0001**	4.1	49, 560	**<0.0001**	5.4	48, 386	**<0.0001**
G × M	Hybrid × Seeding Rate	6.4	28, 560	**<0.0001**	9.8	28, 560	**<0.0001**	1.3	28, 386	0.1841
E × M	Environment × Seeding Rate	3.2	28, 64	**<0.0001**	0.8	28, 64	0.6831	1.2	28, 67	0.2501
G × E × M	Hybrid × Environment × Seeding Rate	1.2	196, 560	**0.0314**	1.7	196, 560	**<0.0001**	0.8	171, 381	0.9216

Abbreviation: DF, numerator degrees of freedom, denominator degrees of freedom.

[a]Ear height analysis also included the ear type category of normal and abnormal ears. From this, other statistically significant results (not listed in this table) included: ear type ($p < .0001$); seeding rate × ear type ($p = 0.0002$); hybrid × ear type ($p = 0.0252$); and environment × hybrid × ear type ($p = 0.0226$).

critical months. Warm and dry weather can suggest stress to the crop, especially if warm temperatures are accompanied by low water availability at critical stages of crop growth and development (Abendroth et al., 2011; Leng & Hall, 2020; Leng & Huang, 2017; Qaderi et al., 2019). However, most of the 2016 survey-affected fields had irrigation, which could have offset low rainfall availability, thus making it more likely that warmer temperatures were the leading stress factor triggering (at least to some degree) abnormal ears in 2016.

Bassu et al. (2014) documented that temperature increases affected 23 modeled yields for maize in four major regions (France, the United States, Brazil, and Tanzania); the size of this effect was about −0.5 Mg per hectare for every °C that increased (compared to the historically associated means for the respective locations). Crop changes in response to temperature variations can be expected from (1) the rate of phenological progress (i.e., from seed germination to crop maturity), (2) the initiation and growth of different organs in plants, (3) crop respiration and photosynthesis, and (4) the process where the crop senesces (Wang et al., 2017). Understanding changes in the direction (i.e., lower or higher) and magnitude (i.e., size) of climate factors affecting crop growth and development for different geographies (Kukal & Irmak, 2018) is necessary. Wang et al. (2017) pointed out the importance and need for more attention to crop simulation on pollination, sterility, and abortion of plant organs affected by rising temperatures which can also be a factor connected to abnormal ears (Ortez et al., 2022b).

3.2 | Crop yields: Hybrids, environments, and seeding rates

The interaction among hybrids, environments, and seeding rates was significant (Table 4; $F_{196, 560} = 1.2$; $p = 0.0314$), suggesting that all three factors were simultaneously important when forming crop yields. What yields better in one environment can be different from what yields better in another, which leads to interaction.

As far as the highest yield results for specific environments (Table 5), Filley 2018 achieved the highest mean yield (16.5 Mg ha^{-1}) with hybrid P1370 (from the check group) and a seeding rate of 84,000 seeds ha^{-1}. For 2019, the highest-yielding hybrid in the same location was P1311 (susceptible) with 124,000 seeds ha^{-1}. That hybrid shift in 2019 may have been influenced by the slightly better weather of 2019 (Figure 2a,e), favoring the susceptible hybrid, which included more precipitation and temperatures closer to the historical mean. The seeding rate (124,000 seeds ha^{-1}) was not significantly different from the 64,000, 84,000, and 104,000 seeding rates, suggesting that similar yields were achieved despite up to a 60,000 drop in seeding rate.

For the Hooper location in 2018, the check hybrid P1370 also resulted in the highest yield (17.6 Mg ha^{-1}) for that environment, under 64,000 seeds ha^{-1} (Table 5). In 2019, the same location achieved the highest yielding result (17.2 Mg ha^{-1}) with the same hybrid but with a slightly higher seeding rate (84,000 seeds ha^{-1}). At the same seeding rate in 2019, susceptible hybrid P1311 yielded almost as well as P1370, with 17.1 Mg ha^{-1}. Overall, the Filley location, both years, had comparable yields to those of the Hooper site, despite Filley being rainfed and Hooper pivot irrigated. This similarity can be partially explained by more seasonal precipitation in Filley than in Hooper for both years (Table 3).

At the western location of this study, Lawrence site (rainfed), yields were not as good as those of Filley and Hooper in both years (Table 5). Lawrence was the site with almost the lowest seasonal precipitation availability in both years of study (Table 3). In 2018, the highest yielding (13.3 Mg ha^{-1}) result was marked by Hybrid P1370 and 84,000 seeds

TABLE 5 Grain yield (expressed in megagrams per hectare, Mg ha^{-1}) differences across eight hybrids (horizontal rows, capital letters) and five seeding rates (vertical columns, lower case letters) for four sites in Nebraska during the 2018 and 2019 growing seasons. Susceptible (Suscept.) and check hybrids are denoted.

Seeding rate (seed ha^{-1})	Grain yield, Mg ha^{-1}															
	P0157 Suscept.	P0339 Check	P0801 Suscept.	P0801[a] Suscept.	P0832 Check	P1311 Suscept.	P1311[a] Suscept.	P1370 Check	P0157 Suscept.	P0339 Check	P0801 Suscept.	P0801[†] Suscept.	P0832 Check	P1311 Suscept.	P1311[†] Suscept.	P1370 Check
	Filley 2018								**Filley 2019**							
44000	12.6Aa	11.9Ab	13.9Aab	12.9Aa	14.3Aa	14.2Aa	13.5Aa	14.3Aa	12.0Cb	12.1Cb	12.8BCa	12.8BCc	13.3BCa	14.9ABa	13.4BCb	16.2Aa
64000	12.4Ba	13.7ABab	16.1Aa	14.7ABa	15.0ABa	14.1ABab	14.7ABa	16.0Aa	14.2Cab	15.2ABCa	14.9BCa	16.0ABCa	14.5BCa	17.1ABa	17.7Aa	15.8ABCa
84000	13.5Ba	14.6ABa	15.0ABab	14.5ABa	14.5ABa	14.9ABa	12.5Ba	16.5Aa	15.2Aa	14.4Aab	14.1Aa	15.6Aab	15.2Aa	16.2Aa	16.7Aa	16.6Aa
104000	13.3Aa	14.5Aa	14.3Aab	14.4Aa	14.4Aa	10.2Bc	14.8Aa	13.9Aa	14.7Ba	15.2ABa	14.1Ba	15.3ABabc	14.7Ba	16.4ABa	17.6Aa	15.9ABa
124000	11.6Ba	14.8Aa	12.7ABb	13.5ABa	13.3ABa	11.6Bbc	13.6ABa	15.4Aa	16.0ABCa	15.4ABCDa	14.0BCDa	13.2Dbc	13.8CDa	16.6ABa	18.1Aa	16.1ABCa
	Hooper 2018								**Hooper 2019**							
44000	11.9Ba	13.2ABa	15.3Aa	14.4ABab	13.4ABa	15.3Aa	13.4ABb	14.8Ab	13.3Bb	13.6Bb	13.9ABab	14.2ABb	14.2ABa	13.3Bb	12.7Bb	16.5Aa
64000	13.5Ba	14.4Ba	14.9ABa	15.6ABab	15.0ABa	15.8ABa	15.0ABab	17.6Aa	15.4Aab	14.9Aab	15.3Aab	15.3Aab	14.9Aa	15.9Aa	15.4Aa	16.6Aa
84000	14.3ABa	13.5Ba	15.8ABa	16.8Aa	15.7ABa	15.6ABa	16.2ABa	16.0ABab	16.2Aa	15.5Aab	16.4Aa	16.9Aa	16.6Aa	16.7Aa	17.1Aa	17.2Aa
104000	12.9Ba	15.6ABa	14.8ABa	15.5ABab	14.4ABa	15.0ABa	15.2ABab	16.3Aab	16.8Aa	16.4Aa	14.9Aab	15.2Aab	16.0Aa	16.3Aa	16.5Aa	16.6Aa
124000	12.6Aa	14.5Aa	13.9Aa	14.1Ab	13.4Aa	14.4Aa	14.1Aab	14.4Ab	16.6Aa	16.6Aa	13.6Bb	13.0Bb	14.9ABa	15.6ABab	15.5ABa	16.3Aa
	Lawrence 2018								**Lawrence 2019**							
44000	11.2Aab	11.4Aab	12.5Aa	12.2Aa	12.2Aa	13.1Aa	11.2Aa	12.9Aa	10.6Aa	10.6Ab	11.8Aa	11.8Aa	11.7Aab	12.3Aa	11.0Aa	12.2Aab
64000	12.2Aab	12.5Aab	13.1Aa	12.7Aa	11.6Aa	12.4Aab	12.7Aa	13.2Aa	11.7Aa	11.9Aab	12.9Aa	12.9Aa	12.8Aa	10.5Aa	12.1Aa	12.3Aab
84000	12.4Aa	12.9Aa	13.1Aa	12.4Aa	12.0Aa	11.3Aabc	12.8Aa	13.3Aa	12.0Aa	12.0Aab	12.8Aa	13.0Aa	12.3Aab	12.2Aa	12.9Aa	13.9Aa
104000	9.6Bb	11.2ABab	10.7ABab	12.3ABa	12.0ABa	9.9ABbc	12.4Aa	12.2ABa	11.4ABa	12.2Aab	11.7Aa	8.9Bb	10.2ABb	10.8ABa	12.3Aa	10.8ABb
124000	10.4ABab	10.2ABb	8.2Bb	11.0Aa	9.7ABa	9.6ABc	10.5ABa	11.3Aa	11.4ABa	13.3Aa	10.6ABa	11.2ABab	11.3ABab	10.5Ba	10.9ABa	11.0ABb
	York 2018								**York 2019**							
44000	13.1Cc	12.8Cb	15.2ABCab	14.5BCab	13.4Cb	17.0ABa	13.7Cb	17.8Aa	13.6ABa	11.9Bb	14.5ABa	13.8ABab	13.8ABa	15.5Aa	15.0Aa	15.0Aa
64000	14.1Cbc	14.9BCab	17.0ABa	16.5ABCa	15.7BCab	18.6Aa	16.4ABCa	19.2Aa	14.4Aa	14.7Aa	15.2Aa	16.1Aa	14.9Aa	16.0Aa	16.0Aa	16.6Aa
84000	17.4Aa	16.4Aa	17.3Aa	16.9Aa	16.5Aa	17.9Aa	17.5Aa	18.9Aa	14.0Ba	15.0ABa	15.8ABa	15.4ABab	14.4ABa	14.9ABa	15.6ABa	17.0Aa
104000	17.8Aa	17.4Aa	15.9Aa	16.6Aa	16.7Aa	17.1Aa	17.8Aa	18.5Aa	15.1Aa	14.8Aa	15.2Aa	14.7Aab	14.2Aa	15.2Aa	15.7Aa	16.0Aa
124000	16.7Aab	16.3ABa	13.2Cb	13.8BCb	16.7Aa	17.6Aa	17.7Aa	17.5Aa	14.8Aa	14.8Aa	14.0Aa	13.1Ab	14.4Aa	15.4Aa	14.8Aa	15.0Aa

Note: Uppercase letters show statistical differences (p-value < 0.05) across hybrids in each environment for the same seeding rate. Lowercase letters show statistical differences (p-value) across seeding rates in each location for the same hybrid.

[a]2016 seed source; all other seeds were sourced from season 2018.

ha^{-1}. The same hybrid and seeding rate yielded the highest in 2019, 13.9 Mg ha^{-1}. Note that the Lawrence site in 2019 had a shorter growing season (187 fewer growing degree days, ∼10% decrease) and less water available (27 mm less in the season, ∼4% decrease) relative to 2018 (Table 3). Although growing conditions were more challenging in 2019, slightly higher yields were achieved, which can speak to hybrid stability characteristics (Changizi et al., 2014).

Following the high-yielding results of longer relative maturity check hybrid P1370 in other locations, in the York site 2018, the highest yield was also achieved with P1370, this time under the 64,000 seeds ha^{-1} (Table 5). In 2019, same location, the same hybrid was the highest-yielding material again but with the 84,000 seeds ha^{-1} treatment. Overall, higher yields were achieved with intermediate seeding rates and hybrids of longer maturities. Duvick (2005) pointed out that genetics and management interact so closely that neither would have produced progress over time without their interaction. Added to this interaction is the contribution of the environmental effect, as recently highlighted by Rizzo et al. (2022). Evidence in the literature suggests that the environment has become more relevant in recent years when trying to maximize corn yields. Duvick (2005) also suggested that the hybrid-by-environment interaction is essential for future genetic gains and plant breeding efforts, which has been evident over the decades.

The highest yielding hybrids in one seeding rate did not equal the same at other seeding rates (e.g., hybrid P1370 was top yielding at 64,000 and 84,000 seeds ha^{-1}, but it did not yield the same when subject to 104,000 and 124,000 seeds ha^{-1}) (Table 5). Genetic improvements in corn have allowed more plant populations to achieve higher yields (Duvick & Cassman, 1999). However, this response is not always linear, and an optimum point is achieved where yields are maximized before yields start to decrease at high seeding rates. Over all the studied conditions, higher yields were achieved with 84,000 seeds ha^{-1}, and lower yields were observed with lower and higher seeding rates. A synthesis analysis of modern corn hybrids from 22 US states and two Canadian provinces from 2000 to 2014 found 84,000 seeds ha^{-1}, the point where corn yields are generally maximized (Assefa et al., 2016). Similar results were found across several hybrids in Iowa (Licht et al., 2019).

The wide range of yield results obtained from hybrids interacting in the differing environments and seeding rates allowed us to study varying yield levels in corn (Table 5) and the differential response that corn ear abnormalities (Table 6) can have. Given the yield and abnormal ear trade-off, interactions between hybrids, environments, and seeding rates can also be responsible for the development of abnormal ears in corn, which is the main focus of this work.

3.3 | Abnormal ears: Hybrids, environments, and seeding rates

Of the total number of individually assessed ears ($n = 63{,}500$ for both years, 2018 and 2019), 8% were abnormal (Figure 3a). These abnormalities spanned all three categories: multi-ear, short-husk, and barbell-ear. Of the 8% abnormal ears, multi-ear showed the highest variability (number of abnormal ears over the total number of assessed ears), which ranged from 0% to 70% of abnormal ears per plot (Figure 3b). Next was short-husk (ranging from 0% to about 50% of abnormal ears per plot), and last, barbell-ear (ranging from 0% to about 20% of abnormal ears per plot). Despite multi-ear presenting the highest variability per plot, the occurrence summary among ear types revealed that most abnormal ears had short-husks (Figure 3c), with about 80% of abnormal ears in this group. After short-husk, the second-highest group was multi-ear (which accounted for about 12% of the total abnormal ears) and, lastly, barbell ears (which accounted for about 8% of the total abnormal ears). Relative to the expected development timing for these ear types, these results would suggest that the potential timing of stress mainly was during the late vegetative stages and close to tasseling and pollination (V18 to R1), as indicated for short-husks which accounted for 80% of all abnormalities.

Abnormal ear percentage results were influenced by a significant three-way interaction of hybrids, environment, and seeding rates (Table 4; $F_{196,\,560} = 1.7$; $p < .0001$); all factors simultaneously affected the number of plants developing abnormal ears. Detailed statistical differences among the levels for all hybrids, seeding rates, and all environments are presented in Table 6. Among the environments, ear abnormalities were differentially driven by hybrids and seeding rates. Some hybrids had more abnormal ear percentages at lower seeding rates, while others had more abnormal ears at higher seeding rates. These trends did not apply to every environment, leading to the interaction.

Hybrid P0801 (a susceptible hybrid) had more abnormalities at higher seeding rates for both hybrid sources (2016 and 2018) in all sites in 2019 but only at Filley and York in 2018, reaching up to 54.1% of ear abnormalities (Hooper, 2019, 124,000 seeds ha^{-1}). On the other hand, hybrid P0157 (another susceptible hybrid) generally had fewer abnormalities at higher seeding rates. However, this result was only observed in three out of the four locations in 2019 (Hooper, Lawrence, and York), with up to 57.3% of abnormalities (Lawrence, 2019, 44,000 seeds ha^{-1}). An overriding finding is that, in general, susceptible hybrids had higher percentages of ear abnormalities relative to their check hybrids counterparts (Table 6). Of the 64 assessed hybrid by environment combinations portrayed in Table 6, general trends showed that

TABLE 6 Abnormal ear percentages (%) differences across eight hybrids (horizontal lines, capital letters) and five seeding rates (vertical lines, lower case letters) for four sites in Nebraska during the 2018 and 2019 growing seasons. Susceptible (Suscept.) and check hybrids are denoted.

Seeding rate (seed ha^{-1})	Abnormal ears, percentage (%)															
	P0157 Suscept.	P0339 Check	P0801 Suscept.	P0801[a] Suscept.	P0832 Check	P1311 Suscept.	P1311[a] Suscept.	P1370 Check	P0157 Suscept.	P0339 Check	P0801 Suscept.	P0801[†] Suscept.	P0832 Check	P1311 Suscept.	P1311[†] Suscept.	P1370 Check
	Filley 2018								**Filley 2019**							
44000	7.1Aa	0.8Aa	0.6Ab	0.9Aa	0.7Aa	1.6Aa	0.0Aa	1.8Aa	10.6Aa	5.2Aa	5.4Ab	9.8Ab	1.7Aa	0.9Aa	3.5Aa	4.4Aa
64000	7.7Aa	0.6Aa	5.6Aab	0.7Aa	1.1Aa	0.6Aa	0.0Aa	1.5Aa	12.5Aa	4.5Aa	10.9Ab	11.6Ab	3.2Aa	2.1Aa	1.4Aa	6.1Aa
84000	6.1Aa	0.5Aa	9.3Aab	7.3Aa	1.0Aa	2.3Aa	0.6Aa	0.9Aa	9.4Ba	2.6Ba	28.1Aa	23.2Aab	7.6Ba	4.5Ba	4.6Ba	9.6Ba
104000	1.9Ba	0.8Ba	9.7Aab	6.6ABa	1.2Ba	3.5ABa	1.0Ba	1.3Ba	6.7Ba	7.1Ba	26.9Aa	28.1Aa	9.5Ba	10.1Ba	8.1Ba	10.9Ba
124000	2.9Ca	1.7Ca	10.1Aa	9.6ABa	3.5ABCa	3.3BCa	1.9Ca	1.0Ca	7.8Ba	5.9Ba	40.3Aa	34.5Aa	9.9Ba	11.3Ba	7.7Ba	11.5Ba
	Hooper 2018								**Hooper 2019**							
44000	4.0Aa	32.8Aa	0.0Aa	1.8Aa	0.8Aa	1.7Aa	0.0Aa	0.0Aa	27.9Aa	6.0Bab	8.2Bc	3.7Bc	5.3Ba	1.8Bbc	1.0Ba	2.8Ba
64000	2.6Aa	3.3Ab	2.3Aa	2.1Aa	0.0Aa	0.0Aa	0.0Aa	0.0Aa	18.0Aab	13.6Aa	7.9Ac	11.2Abc	2.9Aa	1.4Ac	0.0Aa	6.1Aa
84000	4.8Aa	1.0Ab	6.2Aa	6.3Aa	0.4Aa	0.5Aa	0.6Aa	0.0Aa	18.9Bab	5.8CDab	33.0Ab	15.6BCb	5.5 Da	9.6BCDabc	3.6 Da	3.6 Da
104000	1.4Aa	3.1Ab	4.8Aa	10.5Aa	0.0Aa	0.7Aa	1.3Aa	0.0Aa	13.2Bbc	7.7Bab	39.6Aab	36.4Aa	7.5Ba	12.3Bab	7.4Ba	5.1Ba
124000	1.6Aa	1.7Ab	9.3Aa	10.4Aa	0.0Aa	0.9Aa	3.8Aa	0.0Aa	7.4BCc	4.9Cb	54.1Aa	42.4Aa	5.5Ca	14.4Ba	13.8Ba	6.8BCa
	Lawrence 2018								**Lawrence 2019**							
44000	24.2Aa	27.9Aa	1.6Aa	0.9Aa	0.0Aa	0.0Aa	1.1Aa	0.0Aa	57.3Aa	5.9Ba	12.0Bb	6.2Bb	6.5Ba	1.7Ba	1.9Ba	6.4Ba
64000	6.7Aa	3.2Aa	5.6Aa	3.4Aa	0.0Aa	1.2Aa	0.0Aa	0.0Aa	24.1Ab	5.9Ba	11.5ABb	6.0Bb	2.5Ba	4.7Ba	6.9Ba	3.1Ba
84000	0.5Aa	0.5Aa	2.7Aa	3.7Aa	1.3Aa	1.4Aa	1.2Aa	0.5Aa	20.0Ab	2.1Ca	15.8ABb	15.5ABab	3.6Ca	6.3BCa	4.0Ca	3.7Ca
104000	0.0Aa	1.6Aa	10.3Aa	10.8Aa	0.4Aa	1.5Aa	0.9Aa	1.2Aa	5.4BCc	3.3BCa	20.9Aab	22.6Aa	2.3Ca	9.0Ba	7.7BCa	9.3Ba
124000	0.6Aa	0.0Aa	4.8Aa	10.9Aa	1.8Aa	3.4Aa	1.6Aa	4.8Aa	5.6BCc	6.5BCa	29.7Aa	25.6Aa	3.3Ca	10.6Ba	10.6Ba	7.8BCa
	York 2018								**York 2019**							
44000	13.7Aa	8.4Aa	1.6Ac	4.3Ac	0.8Aa	0.0Aa	1.0Aa	0.9Aa	36.8Aa	9.8Ba	3.6Bb	2.8Bd	3.2Ba	1.7Ba	1.8Ba	1.9Ba
64000	19.5Aa	8.2Aa	10.3Abc	9.4Abc	1.8Aa	0.0Aa	0.0Aa	0.7Aa	24.0Aab	9.6Ba	4.9Bb	11.9ABcd	1.2Ba	1.2Ba	0.7Ba	2.8Ba
84000	15.1ABCa	9.4BCDa	21.8Aab	17.5ABb	1.8 Da	6.8CDa	1.2 Da	1.1 Da	14.2Abc	10.6ABa	14.8Ab	22.0Abc	4.5BCa	0.5Ca	3.4BCa	2.8BCa
104000	11.6BCDa	16.7ABCa	22.9Aa	18.5ABb	2.1Ea	7.9CDEa	5.9DEa	2.1Ea	11.2BCc	12.0Ba	41.4Aa	29.8Aab	6.4BCDa	4.4BCDa	2.3 Da	3.5CDa
124000	17.9BCa	10.7CDa	21.2ABab	31.3Aa	2.8Ea	2.2Ea	5.3DEa	3.1Ea	12.9Bbc	12.2BCa	34.7Aa	41.7Aa	5.3CDa	7.6BCDa	2.8 Da	6.2BCDa

Note: Uppercase letters show statistical differences (p-value < 0.05) across hybrids in each environment for the same seeding rate. Lowercase letters show statistical differences (p-value) across seeding rates in each location for the same hybrid.

[a]2016 seed source; all other seed was sourced from season 2018.

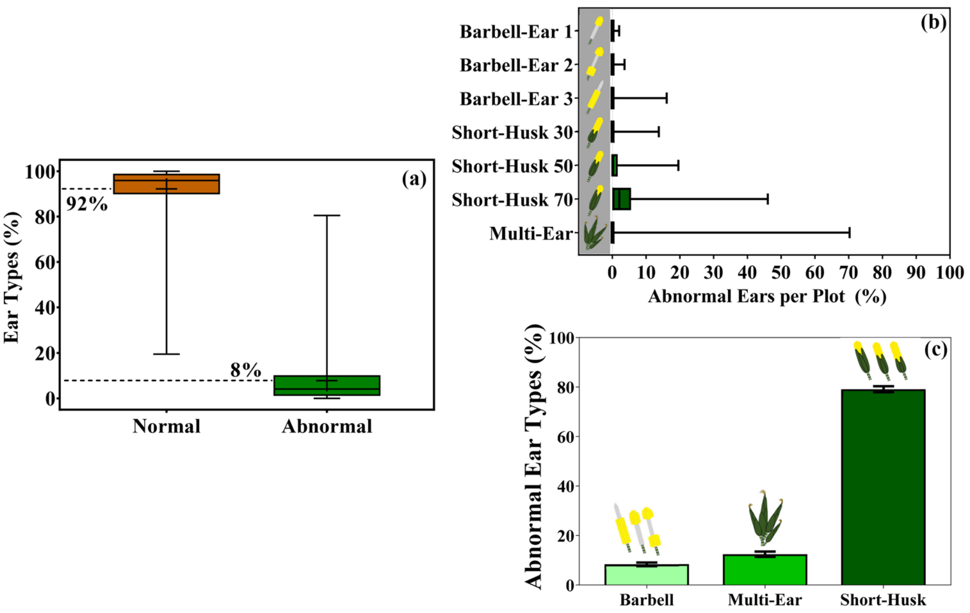

FIGURE 3 Box and whisker plots ([+] shows the mean) for the proportion of normal and abnormal ears in relation to the total number of assessed ears (a). Box and whisker for the proportion of abnormal ears per plot; this is the number of abnormal ears over the total number of assessed ears (b). Mean bars and the standard error of the mean (SEM) for the abnormal ear type distribution in relation to the total number of abnormal ears (c). Four locations, 2018 and 2019, eight hybrids, and five seeding rates in South Central and Eastern Nebraska are included in this summary.

in 39 combinations, abnormal ear percentages increased as seeding rates increased. In 12 combinations, abnormal ear percentages decreased as seeding rates increased, and in 13 combinations, no trend was observed.

In the abnormal ear percentage results, individual plots achieved anywhere from 0% to 80.5% of abnormal ears. It becomes a considerable concern if one walks a plot and identifies such levels of abnormalities. All studied environments had at least one hybrid that exceeded 20% abnormalities (Table 6), except Filley 2018. A survey of 15 farmer fields revealed that individual plants with abnormal ears had yield reductions between 35% and 91% compared to plants grown in the same fields but with normal ears (Ortez et al., 2022c). From these findings, the yield loss from ear abnormalities was suggested to be correlated with the ear symptom and the frequency at which issues occur in the field.

More abnormal ears occurred in 2019 relative to 2018 (Table 6). From the hybrid perspective, three of the genotypes accounted for the majority of abnormal ears across environments: P0801, P0801 (2016 seed), and P0157, which agreed with the initial grouping of these as susceptible hybrids presented in Table 2. Additionally, a hybrid with high percentages of abnormalities in some environments was P0339 (e.g., York location in both years, Hooper 2018, and Lawrence 2018), although based on recommendations and farmer observations, it was considered a check hybrid. These results reinforce the idea of a variation in hybrid ear abnormalities in response to different seeding rates and environments. Hybrids P0801, P0801 (2016 seed), and P0157 had high percentages of abnormal ears, with several cases above 20% of abnormalities and up to 54.1% for P0801 and up to 57.3% abnormalities for P0157. From the susceptible hybrid list (Table 2), P1311 was considered a susceptible hybrid, but the results did not show that clearly. Abnormal ear percentages for this hybrid were consistently below 15%. This could have resulted from its longer relative maturity (113 days) and perhaps due to differences in growth and development when potential crop stressors could have triggered abnormalities (e.g., at less critical timing, relative to other susceptible hybrids).

Although specific dynamics occurred (Table 6), abnormal ears were present in all seeding rates and for several hybrids to some degree. On the lower seeding rate side (e.g., 44,000, 64,000, and 84,000 seeds ha^{-1}), hybrids P0157 and P0339 had the highest number of abnormal ears with a declining trend toward higher seeding rates (Table 6). Hybrids P0801 (both seed sources, 2016 and 2018) showed the lowest ear abnormalities percentages at 44,000 seeds ha^{-1}, with abnormal ear increases at higher seeding rates. The highest percentage was found at 124,000 seeds ha^{-1}. Other hybrids, such as P1370, P0832, P1311, and P1311 (2016 seed), showed low or no abnormalities as seeding rates increased.

A descriptive summary of abnormal ear counts by ear group (Tables S1–S3) indicated that (1) multi-ears were predominant at lower seeding rates (mainly driven by P0157 and P0339 hybrids, see Table S1); (2) barbell-ears were predominant at the higher seeding rates (mainly driven by P0801, 2016 and 2018 seed sources, see Table S2); and (3) short-husks were distributed in most seeding rates above 64,000 seeds ha^{-1} (present in most hybrids, see Table S3). The high-yielding (longer-season) hybrid P1370 or P1311 (Table 5) had minimum to no ear abnormalities in all environmental and seeding rate combinations (Table 6). Abnormal ears decrease grain yields (Ortez et al., 2022a, 2022b, 2022c). In the results presented here, hybrids with more abnormal ears had lower yields (e.g., P0801 and P0157) (Tables 4 and 5). Although this study reported somewhat low percentages of abnormalities overall (2018: about 5%; 2019: about 11%; and 2018–2019 combined: about 8%), the settings studied in this project had up to 80.5% of ear abnormalities in a given plot, and a wide spread of means across conditions that ranged between 0% and 57.3% (Table 6).

Other work in this field has documented variability in abnormal ear results like this. For example, the field survey in 2016 (Ortez et al., 2022c) explored a wide range of growers, yield levels, hybrids, seed companies, locations, and management practices, which helped explain some of the dispersion and variability of results. What is known to this point raises questions about the suitability of hybrids to specific growing conditions and their stability when planted across different environments and management. The environmental conditions expressed in 2016 (warmer and drier weather, Figure 2) could have been conducive to higher overall percentages (26% in affected fields) of abnormal ears relative to 2018 and 2019 (8% combined).

Moreover, the results of this work confirm that hybrids, environment, and seeding rates can change the plant responses of abnormal ears, suggesting that all these factors and their interactions are essential when developing mitigation strategies that can help to minimize abnormal ears. Selecting suitable hybrids and their subsequent management are proactive steps for reducing abnormal ears and achieving higher yields. A specific hybrid yielded the highest when abnormal ears were absent (i.e., P1370). In contrast, the hybrid with the most ear abnormalities (i.e., P0801) was not the highest-yielding; it yielded comparably to several other hybrids that did not show high abnormalities.

Even though P0801 yields were comparable to other hybrids with abnormalities, because of short-husks, grain quality issues can arise due to the exposure of grains to potential pests, disease, and weather factors. The highest-yielding hybrids with minor or hopefully no abnormalities may be selected with the aim of desirable production of grain quality and quantity. Under the conditions studied in this project, hybrid P0801 is not the best option for strategic hybrid selection to mitigate ear abnormalities and pursue higher yields. Nevertheless, P0801 may perform well in environmental conditions that do not favor abnormal ear development in corn. Moreover, it is essential to acknowledge that P0801 and any other hybrids sharing similar backgrounds hold the potential for similar issues in the future, especially if weather like that of 2016 were to occur in future growing seasons.

3.4 | Ear placement: Are abnormal ears associated with lower ear heights?

Earley et al. (1974) reported a trend of secondary developed abnormal ears (multi-ears and barbell-ears) in response to the removal of primary ear shoots and shading plants (90% shading) just before or around the silking stage. In 2016, one of the preliminary hypotheses was that abnormal ears were correlated with the abortion of primary ears (Elmore et al., 2016), from which one can assume lower ear heights. The analysis presented in this section helps to investigate this hypothesis in a non-direct way (i.e., using ear heights instead of ear node numbers), given the labor, time, and resource constraints.

Strachan (2016) pointed out that the placement of primary harvestable ears in corn varies with its genetic background. An overriding result is that ear height differed between normal and abnormal ears. For the most part, abnormal ears had lower placement than normal ears regardless of hybrid, environment, or seeding rate (Figure 4). Some exceptions occurred, as the difference was not significant (e.g., hybrids P0339, P0801, P0832, and P1311 in Filley 2018, Figure 4a). Ear heights of most hybrids varied depending on location and year (Figure 4). This effect suggests the variability expected from environmental changes (Boomsma et al., 2009; Leng & Huang, 2017; Tollenaar & Lee, 2002).

The result of lower ear heights for abnormal ears can support the possibility of primary ear abortion as one of the triggers for abnormal ear development in corn (Ortez et al., 2022b). If the hypothesis is confirmed, future research should investigate what can prevent primary ear loss and secondary abnormal ear development. The study of potential stresses triggering primary ear loss will be critical; some possibilities may include drought, heat, wind, cold, solar radiation, and hormonal responses in corn.

4 | CONCLUSIONS

Abnormal ears (multi-ears, barbell-ears, short-husks) reported from grower fields in the Texas Panhandle to eastern Colorado and east through Kansas, Nebraska, Iowa, and Illinois in 2016 still occur. Of the total number of individually assessed ears in this study, 8% were abnormal. Although the frequency of abnormalities reported here is lower than that of the 2016 Nebraska field survey results (26% of abnormal ears), in some of our studied conditions, ear abnormality percentages were well over 50%. The results of this work confirm the effects of hybrids, environment, seeding rates, and their interactions on the development of abnormal

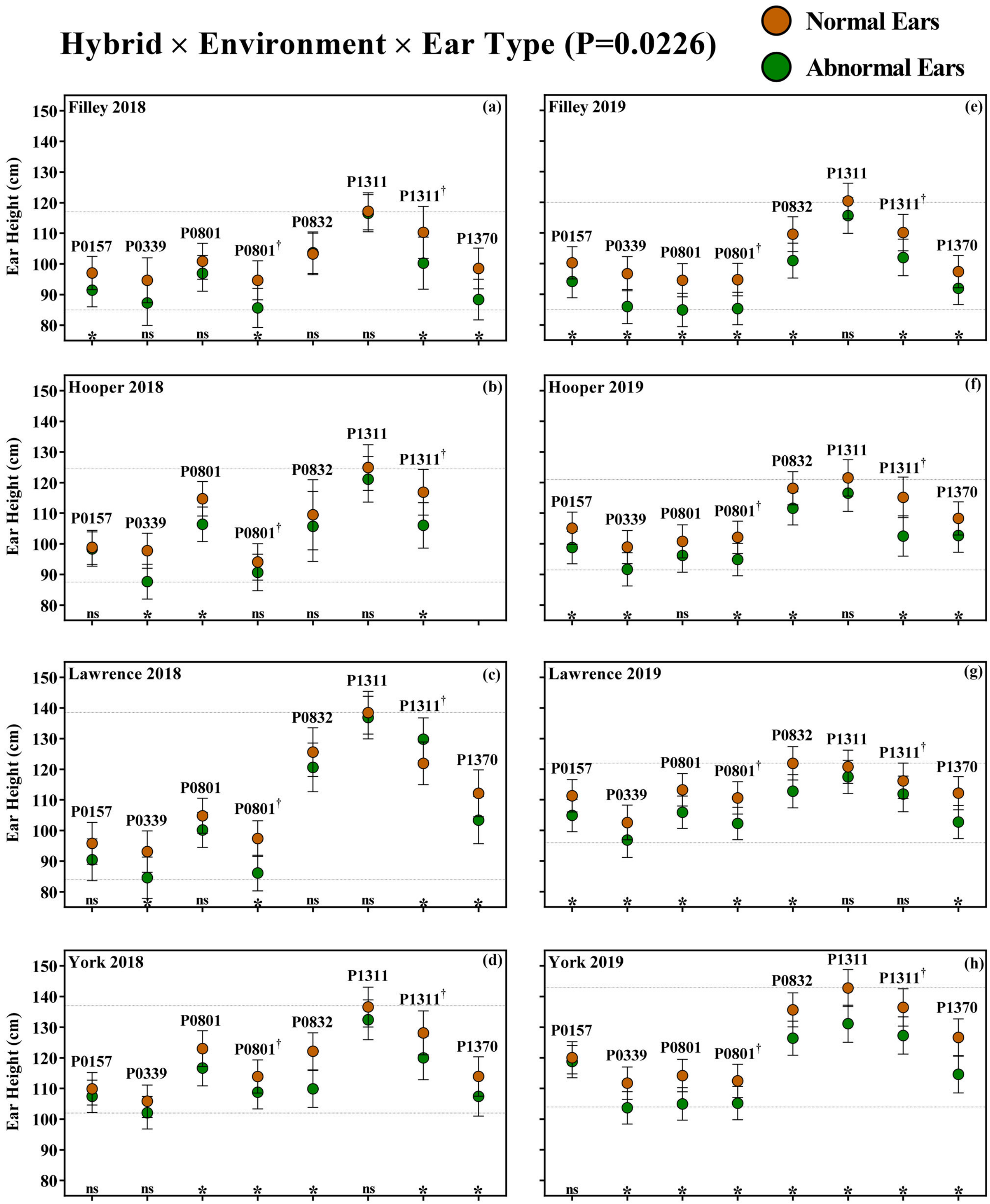

FIGURE 4 Ear height for normal (brown) and abnormal (green) ears for eight hybrids, four locations, and two years: 2018 (a through d), 2019 (e through h). The results show the average of five seeding rates. Hybrid P1370 in Hooper 2018 did not have abnormal ears. The bar for each hybrid shows the upper and lower 95% confidence limit from the least squares means (LSM) analysis. Ear heights were measured at the uppermost viable developed/harvestable ear node. Dotted lines indicate the highest and lowest estimated mean heights across hybrids for each environment. † indicates seed sourced from the 2016 season; all other seed was sourced from season 2018. * indicates a significant difference ($p < 0.05$) between normal and abnormal ears for each hybrid in each environment. ns indicates no significant difference.

ears. Another finding is that abnormal ears were associated with lower heights (relative to normal ears), supporting the hypothesis that primary ear abortion can be a factor in forming abnormal ears, but further research is needed. From the production perspective, lower-yielding hybrids were generally characterized by more ear abnormalities.

The selection of certain hybrids and optimum seeding rates adapted to environmental conditions can help mitigate abnormal ear development in corn while producing higher yields. Abiotic stresses (i.e., warmer and drier weather) occurring during critical ear formation periods can play a crucial role (i.e., from ear formation to silking); this could have been the case for the 2016 abnormal ear widespread. Further studies of weather stress during ear formation and its effects on abnormal ears are still needed. Studying abnormal ears and productivity losses in corn is essential to understanding crop responses in variable geographic distribution and time contexts. Attention to abnormal ear occurrences should be part of breeding programs and screening new genetics, especially exploring risk levels when extreme weather events are likely to occur. It is necessary to continue studying and better understanding the underlying causes and potential mitigation strategies of abnormal ear development in corn.

AUTHOR CONTRIBUTIONS

Osler Ortez: Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; writing—original draft; writing—review and editing. **Justin McMechan**: Conceptualization; funding acquisition; methodology; resources; supervision; writing—review and editing. **Emily Robinson**: Conceptualization; formal analysis; methodology; writing—review and editing. **Thomas Hoegemeyer**: Conceptualization; methodology; writing—review and editing. **Reka Howard**: Conceptualization; methodology; writing—review and editing. **Roger Elmore**: Conceptualization; funding acquisition; methodology; resources; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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