# Identifying Crowding Stress-Tolerant Hybrids in Processing Sweet Corn

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## ABSTRACT

Improvement in tolerance to intense competition at high plant populations (i.e., crowding stress) is a major genetic driver of corn (*Zea mays* L.) yield gain the last half-century. Recent research found differences in crowding stress tolerance among a few modern processing sweet corn hybrids; however, an investigation of interactions with other factors would reveal a deeper understanding of crowding stress tolerance in sweet corn. The objectives of this study were to (i) compare yield, recovery, and processor profitability of sweet corn hybrids grown under conditions of crowding stress, and (ii) determine if an interaction exists between N fertilization and hybrid on crop response to crowding stress. Twenty-six hybrids were grown under suboptimal and supraoptimal N fertilization at 72,000 plants ha$^{-1}$, a level beyond the optimal population of the most crowding stress-tolerant hybrid. Results showed hybrid and N fertilization had no interactive effect on key variables of interest to the sweet corn processing industry, namely green ear mass, recovery, case production, and gross profit margin. Therefore, hybrid rankings were consistent whether the crop was N stressed or not. Relative to the poorest performing hybrid, the highest performing hybrid grown at an elevated population yielded 50% more green ear mass, 61% greater case production, and 71% higher gross profit margin. This work demonstrated a simple method to identify processing sweet corn hybrids with the best tolerance to crowding stress. Significant gains in sweet corn productivity may be realized by growing such hybrids at plant populations higher than currently used.


**In the last century,** superior management practices and improvements in genetics have contributed to a continual rise in field corn yield. Environmental stress tolerance is considered the physiological trait most strongly linked to genetic improvement, whereby modern hybrids have greater tolerance to a host of biotic and abiotic stresses (Tollenaar and Wu, 1999; Duvick, 2005). Of all environmental stresses, tolerance to intense competition at high plant populations (i.e., crowding stress) has improved most in the last 50 yr (Tollenaar and Lee, 2002; Tokatlidis and Koutroubas, 2004). Indeed, maximizing yield of modern field corn production systems requires growing improved hybrids at plant populations that are higher than their predecessors (Duvick, 2005).

Though the subject of considerably less research, sweet corn yields and plant populations also have risen in the last century, albeit at a slower rate than field corn. The few studies investigating relationships between yield and plant populations in sweet corn have focused largely on the fresh market (Morris et al., 2000; Rangarajan et al., 2002). However, different hybrids are used for processing and measurement of "yield" is different from number of marketable ears per unit area. Furthermore, processing sweet corn accounts for a majority of the nation's sweet corn hectareage, with approximately one-half of the processing hectareage in the midwestern states of Illinois, Minnesota, and Wisconsin (NASS, 2014). Relative to field corn, high labor requirements to accurately measure yield is a major reason for the paucity of research on processing sweet corn yield, including work related to plant populations (Williams, 2014). A research method to limit the number of experimental units in field trials, yet shed light on crowding stress tolerance in sweet corn, is needed.

Recent research indicates variable tolerance to crowding stress in processing sweet corn. As an example, Williams (2012) found that plant populations needed to maximize green ear mass of six widely used hybrids ranged from 48,100 to 70,200 plants ha$^{-1}$. Consistent with findings in field corn, there was a positive relationship between optimal plant populations of individual hybrids and their yield potential (reference Fig. 1A). In the interest of comparing hybrids, crop response under high plant populations would reveal crowding stress tolerance. Moreover, some of the most crowding stress-tolerant hybrids appear to be under-planted in the Midwest. For instance, the distribution of optimal plant populations of one hybrid (mean = 70,200 plants ha$^{-1}$) identified in research trials exceeded the distribution of plant populations observed in growers' fields (mean = 53,300 plants ha$^{-1}$) of that hybrid (from Williams, 2012).

Does N fertilization affect hybrid tolerance to crowding stress? This question has been poorly studied in sweet corn; however, field corn response to crowding stress and N fertilizer can be hybrid specific. Newer field corn hybrids use N more efficiently than older hybrids (Carlone and Russell, 1987; O'Neill et al., 2004). Furthermore, hybrids within the same era responded differently to a combination of N fertilizer and crowding stresses

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**Abbreviations:** sh2, shrunken-2.

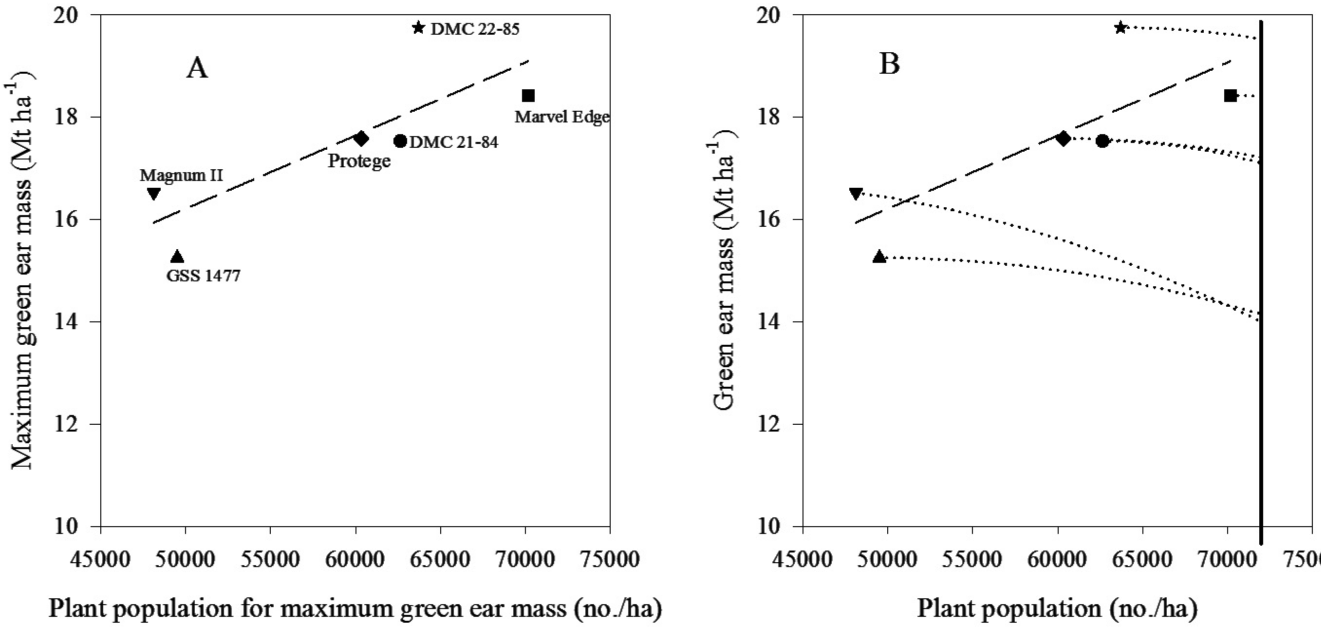


Fig. 1. (A) Relationship between plant population for maximum green ear mass of six shrunken-2 processing hybrids and their corresponding maximum green ear mass (adapted from Williams 2012). Each symbol represents a different hybrid, and the long dashed line is the linear relation between variables. (B) This is the same graph, including yield response to plant populations above the optima (dashed lines) of each hybrid. The solid vertical line at 72,000 plants ha$^{-1}$ is the target population used in the present study.

(Carlone and Russell, 1987). Boomsma et al. (2009) argue the importance of simultaneous improvement in genetic factors affecting tolerance to both crowding stress and N stress.

The objectives of this study were to (i) compare yield, recovery, and processor profitability of sweet corn hybrids grown under conditions of crowding stress, and (ii) determine if an interaction exists between N fertilization and hybrid on crop response to crowding stress.

## MATERIALS AND METHODS

### Germplasm

Early in 2012, vegetable processing companies were asked to identify hybrids important to their sweet corn production portfolio. Seed of hybrids was obtained from seed companies or vegetable processing companies with internal breeding programs. In addition, companies were given the opportunity to submit additional, including pre-commercial, hybrids for the test. A total of 26 processing hybrids, all with the shrunken-2 (sh2) endosperm mutation, were obtained from eight sources (Table 1).

### Experimental Approach

A single experimental protocol was used in 2012, 2013, and 2014 at the University of Illinois Vegetable Crop Research Farm near Urbana, IL (40°4′ N, 88°12′ W, elevation 222 m). The experiment followed the soybean [*Glycine max* (L.) Merr.] phase of a sweet corn–soybean rotation; therefore, a different field was used each year. Soil in all fields was a Flanagan silt loam (fine, smectitic, mesic Aquic Argiudoll) averaging 3.0% organic matter and pH of 6.7.

The treatment design was a factorial arrangement of hybrids and two N fertilization treatments. Based on a fertility recommendation of 135 kg N ha$^{-1}$ (Fritz et al., 2010; Laboski and Peters, 2014), two N fertilization treatments were created; a suboptimal rate of 67 kg N ha$^{-1}$ and a supraoptimal rate of 202 kg N ha$^{-1}$. Within 1 wk of planting, N was applied as urea and immediately incorporated with a field cultivator. Planting dates were 17, 15, and 20 May of 2012, 2013, and 2014, respectively.

The experimental design was a split plot randomized complete block with four replications. The N fertilization treatments were assigned to main plots measuring 9 by 87 m. Hybrids were assigned to subplots consisting of four rows on 76 cm spacing, measuring 3 by 9 m. As a preventative measure for control of insect pests, tefluthrin ((1*S*,3*S*)-*rel*-2,3,5,6-Tetrafluoro-4-methylbenzyl 3-((*Z*)-2-chloro-3,3,3-trifluoroprop-1-en-1-yl)-2,2-dimethylcyclopropanecarboxylate) was applied in a t-band at planting. Weed control was accomplished by a single interrow cultivation, handweeding, and selective herbicides, including atrazine [6-chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine] plus metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] applied pre-emergence.

The target plant population of 72,000 plants ha$^{-1}$ was selected because it exceeds the optimal plant population of the most crowding stress-tolerant hybrid identified in recent research (Fig. 1B). As such, hybrids with optimal plant populations near the target population continue to yield well; however, yields decline for hybrids with optimal plant populations far below the target population (i.e., lower tolerance to crowding stress). Hybrids were over-seeded 35% at planting and hand thinned to 72,000 plants ha$^{-1}$ after seedling emergence. During thinning, significant effort was made to create a stand with in-row spacing as uniform as possible. Stand counts were made after thinning to confirm final population. Water was applied as needed through an overhead irrigation system to facilitate crop growth during abnormally dry periods. Furthermore, permethrin [3-phenoxybenzyl (1RS)*cis*,trans-3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropanecarboxylate] was foliar applied at a rate of 112 g a.i. ha$^{-1}$ as needed to control insect pests, primarily Western corn rootworm (*Diabrotica virgifera virgifera*) and corn earworm (*Helicoverpa zea*).

Table 1. Basic information of the 26 shrunken-2 processing sweet corn hybrids used in field trials near Urbana, IL.

| Hybrid | Kernel color | Maturity† | Company |
|---|---|---|---|
| | | d | |
| 5808 | yellow | 72 | Seminis |
| AC 610 | yellow | 78 | Abbott and Cobb |
| ACX SS1508DY | yellow | 77 | Abbott and Cobb |
| Basin | yellow | 79 | Seminis |
| CSHYP9–360 | yellow | 80 | Crookham Company |
| DMC 21–84 | yellow | 78 | Del Monte Foods |
| DMC 22–85 | yellow | 79 | Del Monte Foods |
| DMX 21–30 | yellow | 74 | Del Monte Foods |
| DMX 22–90 | yellow | 78 | Del Monte Foods |
| Fortitude | yellow | 81 | Crookham Company |
| Galaxy | yellow | 77 | Crites Seed |
| GG 605 | yellow | 74 | General Mills |
| GG 641 | yellow | 78 | General Mills |
| GSS 1453 | yellow | 80 | Syngenta |
| GSS 1477 | yellow | 78 | Syngenta |
| GSS 2259P | yellow | 83 | Syngenta |
| Magnum II | yellow | 80 | Syngenta |
| Marvel Edge | yellow | 75 | Crookham Company |
| Overland | yellow | 80 | Syngenta |
| Protégé | yellow | 76 | Syngenta |
| Rana | yellow | 74 | Crookham Company |
| SHY6RH1365 | yellow | 77 | Seminis |
| WSS 3681 | white | 79 | Syngenta |
| XTH 1079 | yellow | 74 | Illinois Foundation Seeds |
| XTH 1679 | yellow | 74 | Illinois Foundation Seeds |
| ZHY 1027 | yellow | 74 | Crites Seed |

† Maturity based on days from planting to ~76% kernel moisture in the field trials, averaged across environments.

### Data Collection

All crop data was taken from the center two rows of each subplot. At the onset of anthesis, the number of plants with emerged silks were counted daily until at least 50% of plants had silked; herein identified as the mid-silk date. Near mid-silk, number of ear shoots per plant was recorded based on 10 plants per subplot. Each hybrid was harvested 20 to 22 d after mid-silk. Marketable ears, measuring ≥4.5 cm in diameter, were hand-harvested over the center 6 m length of each subplot. Marketable ear number and green ear mass were recorded. Twelve marketable ears from each subplot were randomly taken for further analyses. Ears were hand husked, weighed, and measured for ear length (butt to tip) and filled ear length (well-developed kernels). Kernels were cut from the cob with an industry-grade hand-fed corn cutter (A&K Development, Eugene, OR). Cob mass was recorded. Kernel mass was calculated as the difference in husked mass and cob mass, then adjusted to 76% kernel moisture. Case production was calculated as the number of cases per hectare, using 6.13 kg of kernels per case. Recovery was calculated as the percentage of kernel mass represented in the green ear mass sample.

Processing sweet corn is grown under contract between a vegetable processing company and a grower. Often the processing company determines several critical aspects of the contract, including hybrid and plant population. The grower is compensated based on the tonnes of green ear mass harvested per unit area. To gain a more complete picture of hybrid performance to the processor, gross profit margin to the processor should be quantified (Williams, 2012). Gross profit margin was calculated as the product of case production and wholesale cash price of canned sweet corn (US$12.75 case$^{-1}$), minus the contract cost to the grower ($122 Mt$^{-1}$). Estimates of wholesale case price of corn and contract cost were obtained from the vegetable processing industry (Nick George, Midwest Food Processors Association; personal communication, 2012).

### Data Analysis

Despite overseeding plots 35%, occasionally seedling emergence failed to achieve the target of 72,000 plants ha$^{-1}$. An accurate, uniformly high plant population across all hybrids was essential to addressing the objectives of this work. Therefore, plots with plant populations below 90% of the target were removed before analyses. Percentage of plots removed due to inadequate plant populations were 5, 2, and 14% in 2012, 2013, and 2014, respectively.

Green ear mass, recovery, case production, and gross profit margin were considered "processor variables", while ear shoots per plant, marketable ears per plant, ear length, and filled ear length were considered "ear traits". To evaluate the significance of hybrid, N fertilization, and their interaction on processor variables and ear traits, data were analyzed using the Mixed procedure of SAS (Version 9.3. SAS Institute Inc., Cary NC). Fixed effects included hybrid, N fertilization, and their interaction. Random effects included year and replicate nested within year. Before analysis, diagnostic tests of residuals showed data complied with assumptions of homoschedasticity and normality.

With 26 hybrids, 325 pairwise hybrid comparisons are possible for each response variable. However, interest lies in the top-performing hybrids under well managed conditions, not necessarily all possible hybrid combinations or with inadequate N fertilization. Therefore using the supraoptimal N fertilization treatment, hybrids were ranked according to gross profit margin, the single most important processor variable. Gross profit margin and ear traits of the top 10 ranked hybrids were reanalyzed separately from remaining hybrids. This reduced the number of pairwise hybrid comparisons to 45 and increased the resolution of detecting true differences between pairs of top-performing hybrids. Where main effects were significant, means were compared using the protected, Bonferroni-corrected multiple comparison procedure (Neter et al., 1996).

## RESULTS AND DISCUSSION

### Seasonal Conditions

The characteristic variable growing conditions of the Midwest were observed over the 3 yr of study, as evidenced by air temperature and rainfall patterns. For instance, the 2012 growing season was among the hottest and driest on record in central Illinois. Mean monthly air temperatures exceeded the 30-yr mean by 0.8 to 4.8° (Table 2). Anthesis occurred in July, and 27 of 31 d that month exceeded 32°C, 7d of which also exceeded 38°C. Abnormally low rainfall in June and July were compensated with irrigation, bringing total water supply near normal. Air temperatures in 2013 were 1.8 to 1.4°C above the 30-yr mean in May and June; otherwise, temperature and water supply were near normal (Table 2). In contrast, 2014 was wet, with below-average temperatures during anthesis in July.

## All Hybrids

Prolificacy, the phenotypic expression of multiple ears per plant, was not observed. Mean number of marketable ears per plant among hybrids ranged from 0.58 to 0.90 (data not shown). Prolificacy occurs when environmental conditions favor development of subapical ears in prolific hybrids. Minimal competition among neighboring plants (i.e., lack of crowding stress) favors prolificacy (Hallauer, 1974; Svečnjak et al., 2006). Although both prolific and non-prolific field corn hybrids are commercially available, processing sweet corn appears to be dominated by prolific hybrids (Williams, 2014). Prolificacy was observed among widely used processing hybrids at low populations (<45,000 plants ha$^{-1}$), but rarely at higher populations (>60,000 plants ha$^{-1}$; Williams, 2014). Absence of multiple marketable ears per plant in the present study indicates the target plant population of 72,000 plants ha$^{-1}$ resulted in some crowding stress to all hybrids.

With regards to processor variables, hybrid had no effect on crop response to N fertilization. Specifically, hybrid and N fertilization did not have an interactive effect on green ear mass, recovery, case production, or gross profit margin ($P$ = 0.100 to 0.719; Table 3). Hybrid also did not influence crop response to N fertilization in two of the four ear traits (Table 3). The lack of an interactive effect between N fertilization and hybrid on processor variables demonstrates that hybrid rank at suboptimal N fertilization remains relatively consistent at supraoptimal N fertilization.

As expected, adequate N fertilization improved sweet corn production. With the exception of ear shoots per plant, all response variables differed between N treatments ($P \leq 0.008$; Table 3). Compared to suboptimal N fertilization, supraoptimal N fertilization improved green ear mass 6.2 Mt ha$^{-1}$, recovery 1.4%, case production 360 cases ha$^{-1}$, and gross profit margin \$3,740 ha$^{-1}$. Boomsma et al. (2009) found that tolerance to crowding stress is largely dependent on adequate N fertilization. The purpose of the two N fertilization treatments in this work was to determine if an interaction exists between N fertilization and hybrid on sweet corn response to crowding stress. Therefore, a supraoptimal N fertilization treatment, while excessive, was used to contrast suboptimal N fertilization. Nonetheless, overfertilizing processing sweet corn with N appears to be a common problem (Ruark et al., 2011; Laboski and Peters, 2014).

Hybrids responded differently to conditions of crowding stress. The main effect of hybrid was significant ($P$ < 0.001) for all processor variables and ear traits (Table 3). Since underfertilization in growers' fields appears rare in North America, remaining discussion will examine hybrid response when N is less likely to be limited (i.e., supraoptimal N fertilization).

The highest yielding hybrid produced 50% more green ear mass than the lowest yielding hybrid. Green ear mass ranged from 16.0 Mt ha$^{-1}$ for WSS 3681 to 24.1 Mt ha$^{-1}$ for DMC 22-85 (Fig. 2A). Processing sweet corn yields in the Midwest over the 3 yr of this study (2012–2014) averaged 17.1 Mt ha$^{-1}$ (NASS, 2014). The *highest* yielding fields in Illinois in 2005 to 2007 averaged 17.5 Mt ha$^{-1}$ (Williams et al., 2009). Based on trials and field surveys, Williams (2012) showed crowding stress tolerant hybrids are being under-planted in the Midwest. On-farm yields fall at the low end of the range of yields observed in the present work, suggesting processing sweet corn productivity could be increased with wider adoption of crowding stress-tolerant hybrids planted at populations higher than currently used.

Table 2. Mean monthly air temperature, water supply, and departure from the 30-yr mean (1981–2010). Data provided by the Illinois State Climatologist's Office, a part of the Illinois State Water Survey (ISWS) located in Champaign and Peoria, IL, and on the web at www.isws.illinois.edu/atmos/statecli.

| | | Air temperature | | Water supply | | Departure from mean | |
|---|---|---|---|---|---|---|---|
| Year | Month | Min. | Max. | Rainfall | Irrigation | Temperature | Water supply |
| | | °C | | cm | | °C | cm |
| 2012 | May | 13.6 | 27.3 | 9.0 | 0.0 | 3.8 | −1.5 |
| | June | 15.5 | 29.6 | 4.6 | 4.6 | 0.8 | −1.8 |
| | July | 20.6 | 34.9 | 1.4 | 8.7 | 4.8 | −1.3 |
| | August | 16.8 | 30.7 | 14.2 | 0.0 | 1.8 | 4.9 |
| 2013 | May | 12.1 | 24.0 | 11.8 | 0.0 | 1.4 | 1.3 |
| | June | 16.2 | 27.9 | 13.5 | 1.9 | 0.3 | 4.4 |
| | July | 17.4 | 28.3 | 8.8 | 1.8 | −0.1 | −0.8 |
| | August | 16.9 | 29.5 | 1.2 | 0.0 | 1.3 | −8.1 |
| 2014 | May | 11.7 | 23.0 | 10.5 | 0.0 | 0.8 | 0.0 |
| | June | 17.6 | 28.6 | 22.9 | 0.0 | 1.4 | 11.8 |
| | July | 15.8 | 27.1 | 20.3 | 0.0 | −1.6 | 8.9 |
| | August | 18.1 | 28.7 | 3.6 | 0.0 | 1.5 | −5.8 |

Table 3. Significance ($P$) of hybrid (26 shrunken-2 processing hybrids) and N level (suboptimal and supraoptimal fertilization) on green ear mass, recovery, case production, gross profit margin, ear shoots, marketable ears, ear length, and filled ear length for sweet corn grown under conditions of crowding stress (72,000 plants ha$^{-1}$) over a 3-yr period near Urbana, IL.

| Factor | Green ear mass | Recovery | Case production | Gross profit margin | Ear shoots plant$^{-1}$ | Marketable ears plant$^{-1}$ | Ear length | Filled ear length |
|---|---|---|---|---|---|---|---|---|
| Hybrid | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| N | <0.001 | <0.001 | <0.001 | <0.001 | 0.010 | <0.001 | 0.008 | <0.001 |
| Hybrid × N | 0.362 | 0.719 | 0.123 | 0.100 | 0.407 | 0.025 | 0.301 | 0.019 |

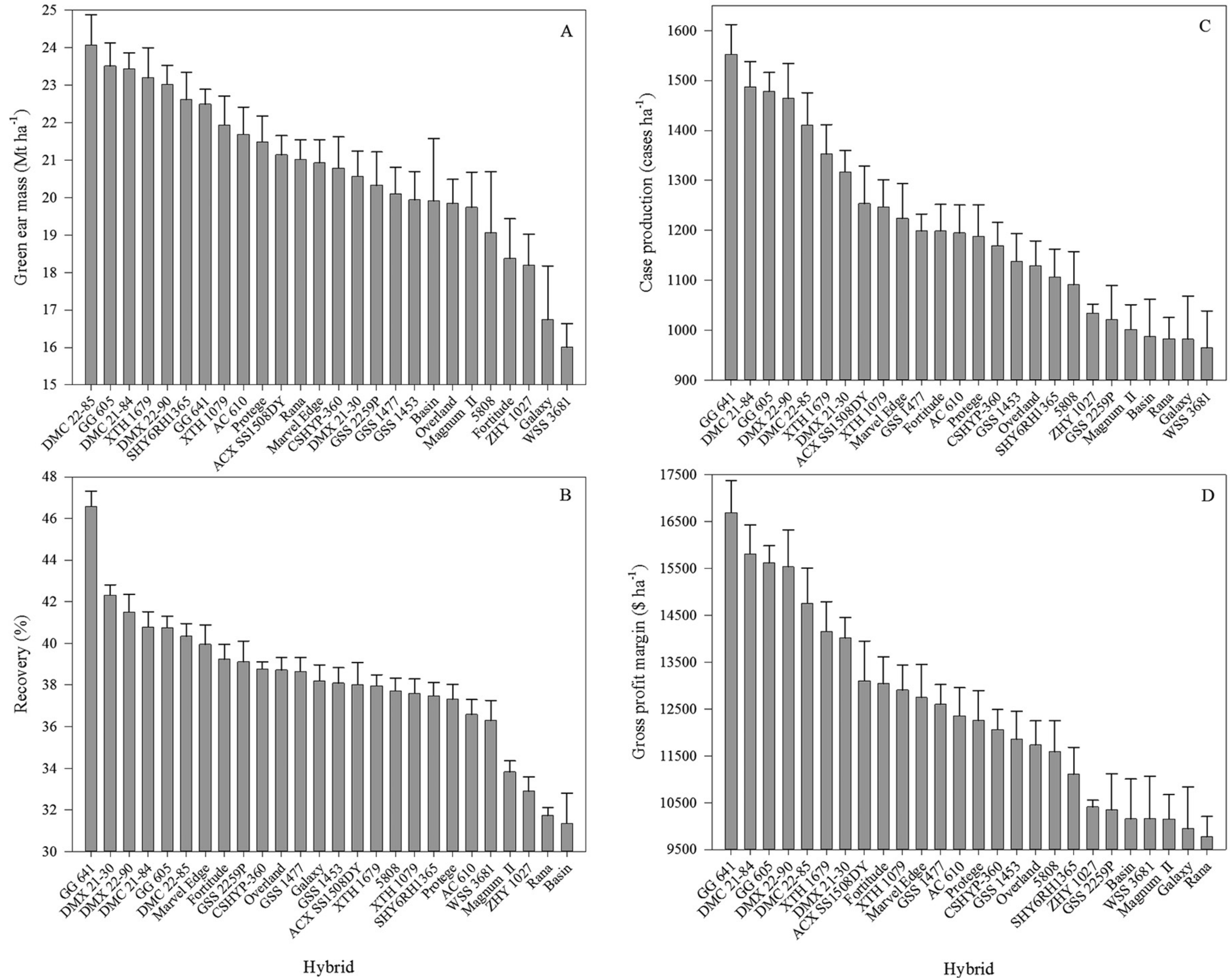


Fig. 2. Mean (A) green ear mass, (B) recovery, (C) case production, and (D) gross profit margin of 26 shrunken-2 processing hybrids grown under conditions of crowding stress (72,000 plants ha$^{-1}$) with supraoptimal N fertilization near Urbana, IL. Standard error bars are included. Means of N fertilization treatments are significantly different for all response variables ($P < 0.001$).

Table 4. Ear traits of top 10 shrunken-2 processing sweet corn hybrids, based on gross profit margin, grown under supraoptimal N fertilization and crowding stress (72,000 plants ha$^{-1}$) in field trials over a 3-yr period near Urbana, IL. Means separation was determined by Bonferroni-corrected multiple comparisons at $P < 0.05$.

| Rank | Hybrid | Gross profit margin | Ear shoots plant$^{-1}$ | Marketable ears plant$^{-1}$ | Ear length | Filled ear length |
|---|---|---|---|---|---|---|
| | | US$ ha$^{-1}$ | ——— no. plant$^{-1}$ ——— | | ——— cm ——— | |
| 1 | GG 641 | 16,700a | 1.9a | 0.93ab | 20.0b | 17.8b |
| 2 | DMC 21-84 | 15,800ab | 1.5a | 0.88ab | 19.0c | 17.9b |
| 3 | GG 605 | 15,600abc | 1.9a | 0.95a | 19.1c | 17.8ab |
| 4 | DMX 22-90 | 15,500abc | 1.7a | 0.88ab | 21.5a | 18.2ab |
| 5 | DMC 22-85 | 14,700abc | 2.0a | 0.91ab | 19.3c | 17.7b |
| 6 | XTH 1679 | 14,200abc | 2.0a | 0.91ab | 19.2c | 18.2ab |
| 7 | DMX 21-30 | 14,000abc | 2.3a | 0.89ab | 19.0c | 17.2b |
| 9 | Fortitude | 13,300bc | 2.4a | 0.84 b | 18.8c | 17.3b |
| 8 | ACX SS1508DY | 13,100bc | 1.9a | 0.84 b | 20.5b | 18.9a |
| 10 | XTH 1079 | 12,800c | 2.1a | 0.90ab | 19.1c | 18.3ab |

Recovery of most hybrids ranged from 36 to 42%; however, some exceptions were observed. Four hybrids had recovery <36%–Magnum II, ZHY 1027, Rana, and Basin (Fig. 2B). In contrast, the hybrid with the highest recovery exceeded 46%; specifically, GG 641. Recovery is important to the sweet corn processor for several reasons. All else being equal, a higher recovery enables the processor to purchase less green ear mass to achieve a desired level of case production. In addition, ear components other than recoverable kernel mass are waste, for which disposal comes at a cost. The consistent, exceptionally high recovery of GG 641 appears unique among hybrids tested, and improving such a trait in other hybrids would be desirable for the sweet corn processing industry.

With regards to case production, the highest yielding hybrid produced 61% more cases than the lowest yielding hybrid. Case production ranged from 965 cases ha$^{-1}$ for WSS 3681 to 1552 cases ha$^{-1}$ for GG 641 (Fig. 2C). A majority of processing hybrids available in North America have yellow kernels (Pataky et al., 2011). As such, all but one entry in this trial has yellow kernels. The exception was WSS 3681, which has white kernels. Kernel color is a simply inherited trait, with white recessive to yellow (Tracy, 1993). Conceivably, genetic improvement in yellow kernel hybrids has been greater than development of white kernel lines. Poor crowding stress tolerance of WSS 3681 may be a reflection of relatively lower investment in germplasm improvement of white kernel sweet corn. Alternatively, WSS 3681 may be poorly adapted to the Midwest if it was developed for use exclusively in the southern United States, where white kernels are preferred (Tracy, 1993).

Gross profit margin, as determined in this study, is the single most integrative measure of hybrid performance for the processor. Not only does the metric account for the cost of green ear mass of a given hybrid, but also the value of the hybrid's case production. The most profitable hybrid, GG 641, had a 71% higher gross profit margin than the least profitable hybrid, Rana (Fig. 2D). Williams (2012) reported optimal plant population densities of several hybrids identified by processors that are widely used in the Midwest, including GSS 1477 and Protégé. These hybrids were included in the current study. The most profitable hybrid in this study, GG 641, was 32% more profitable than GSS 1477 and 36% more profitable than Protégé. Although the optimal plant population of GG 641 has not been reported, optimal plant populations of GSS 1477 and Protégé are well below 72,000 plants ha$^{-1}$ (Williams, 2012), the population used in the present work. Nonetheless, if field corn serves as a valid example to improving sweet corn productivity, future sweet corn hybrids will be planted at higher populations than present, in large part due to improved stress tolerance, particularly to crowding stress (Tollenaar and Wu, 1999; Duvick, 2005).

## Top Ten Hybrids

Differences in crowding stress tolerance among hybrids were detected not only among all 26 hybrids, but also among the top 10 hybrids. Based on means separation, the seven highest ranked hybrids had similar gross profit margins (Table 4). Interestingly, most of these hybrids are from two sweet corn breeding programs owned by vegetable processors; specifically, General Mills and Del Monte Foods. Crowding stress tolerance in sweet corn is a heritable trait (Shelton and Tracy, 2013). Trends in plant populations, used by growers the last 50 yr (Mack, 1972; Ferro et al., 1998), indicates there has been selection for crowding stress tolerance in sweet corn, whether directly or indirectly. However, wide variability in optimal plant population and maximum yield among modern hybrids indicates crowding stress tolerance has not been a major breeding objective industry wide (Williams, 2012). Indeed, two decades ago the main breeding objectives for processing sweet corn focused on eating quality, insect and pathogen resistance, and cold and drought tolerance (Tracy, 1993). Nonetheless, the current research shows progress, and opportunity, in crowding stress tolerance.

Measurement of sweet corn "yield" in research and development trials historically has been quantified with green ear mass. However, recent research has shown that fresh kernel mass is a much better predictor of both case production and gross profit margin (Williams, 2014). Only in the last few years have most seed companies began obtaining fresh kernel mass in yield trials (R. Teyker, personal communication, 2014). In contrast, General Mills and Del Monte Foods have been measuring fresh kernel mass in yield trials for decades (P. Richter, S. Otto, personal communication, 2014). Perhaps as measurement of kernel mass and recovery become more widespread in sweet corn breeding programs, the resolution of detecting crowding stress tolerance in processing sweet corn will become clearer.

While some differences in ear traits were observed among the top 10 hybrids, those differences were generally minimal. Marketable ears per plant ranged from 0.84 to 0.95, ear length ranged from 18.8 to 21.5 cm, and filled ear length ranged from 17.2 to 18.9 cm (Table 4). Individual ear traits are generally poor predictors of processor variables. In a meta-analysis of various datasets from 22 environments over 8 yr on 31 processing hybrids, Williams (2014) found correlations between case production and ear traits ranged from 0.33 to 0.68. While such correlations are statistically significant, ear traits do not serve as a useful metric to discriminate among hybrids with differential tolerance to crowding stress.

The standard method to quantify crowding stress tolerance among hybrids in field corn, with numerous plant population treatments, is not practical for comparing more than a few sweet corn hybrids. For instance, Mansfield and Mumm (2014) evaluated crowding stress tolerance of 36 field corn hybrids by using six plant populations in three replicates for a total of 648 experimental units in each of 3 yr. While clearly a large field experiment, machine harvest after physiological maturity enabled the research. In contrast, harvest timing of sweet corn must occur over a narrow window of time, often ears are hand harvested, and processing ears is time-sensitive and laborious (Williams, 2014). By using a single, high plant population in the current research, selected above the highest optimal population yet observed, relative tolerance to crowding stress could be quantified for 26 sweet corn hybrids.

Currently, the sweet corn processing industry in the Midwest is utilizing plant populations consistent with the average sweet corn hybrid (Williams, 2012). However, processing hybrids vary greatly in their tolerance to crowding stress. Relative to the poorest performing hybrid in the present study, the highest performing hybrid grown at an elevated population yielded 50% more green ear mass, 61% greater case production, and 71% higher gross profit margin. This work demonstrates a simple method to identify processing sweet corn lines with the best tolerance to crowding stress, which may be useful as more sweet corn breeding programs and vegetable processing industry moves toward the use of higher plant populations. Significant gains in sweet corn productivity may be realized by growing such hybrids at plant populations higher than currently used. The sweet corn industry would benefit from additional research that quantifies optimal plant populations of crowding stress-tolerant hybrids, particularly under the wide range of management tactics and environmental conditions observed in growers' fields.

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