Field Crops Research 128 (2012) 55–61

Contents lists available at SciVerse ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Agronomics and economics of plant population density on processing sweet corn

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ARTICLE INFO

Article history:
Received 8 November 2011
Received in revised form
12 December 2011
Accepted 14 December 2011

Keywords:
Competition
Development
Growth
Stress tolerance
Yield

ABSTRACT

A detailed analysis of the effect of plant population density (hereafter called 'populations') on processing sweet corn is lacking in the peer-reviewed literature. Therefore, field experiments were conducted utilizing six hybrids commonly grown in North America, one of several locations where sweet corn is grown for processing globally. The objectives were to: (1) quantify the effects of population and commercial hybrid on sweet corn growth, development, ear traits, and yield, (2) determine populations for maximum yield for growers and maximum gross profit margin for processors, and (3) compare populations for maximum yield and maximum gross profit margin to populations observed in processing sweet corn fields. Increasing populations from 43,000 to 86,000 plants ha^{-1} linearly increased canopy density, light interception, and length of the vegetative period, while linearly decreasing filled ear length and recovery – the percent of kernel mass represented in green ear mass. The processing hybrids used in this study differed not only in yield potential, ranging from 15.3 to 19.8 Mt ha^{-1}, but also in their ability to tolerate high populations. In general, higher-yielding hybrids performed best at higher populations. Based on surveys of growers' fields in North America, populations average 56,000 plants ha^{-1}, which was consistent with the average population for maximum gross profit margin for processors ($9900 ha^{-1}). Both growers and processors could realize increased yield and profit by using certain hybrids at populations higher than currently used.

1. Introduction

Sweet corn is grown for processing in many locations, including Australia, Brazil, Canada, China, Europe, New Zealand, South Africa, and the United States of America. A detailed analysis of the effect of plant population density (hereafter called 'populations') on processing sweet corn does not exist in the peer-reviewed literature. Such research would serve as the basis for understanding the dynamics of interplant competition and developing recommendations on populations for optimal yield. While numerous authors have examined various aspects of population-mediated effects in field corn (e.g. Nafziger, 1994; Stanger and Lauer, 2006), this information has little application to sweet corn because of the many different genes that affect all phases of plant growth, the different crop production practices used, and the different traits that are important to yield and marketability (Azanza et al., 1996; Treat and Tracy, 1994).

Some results have been published on the effect of populations on fresh market sweet corn in Australia (Rogers and Lomman, 1988) and North America (Morris et al., 2000; Rangarajan et al., 2002). However, fresh market production generally utilizes different hybrids than sweet corn grown for processing. Also, the metric of crop performance in all of these fresh market studies is number of marketable ears produced per unit area. For processing sweet corn, important metrics include mass of ears produced per unit area and percentage of ear mass accounted by recoverable fresh kernel mass, hereafter called 'recovery'. Mack (1972) evaluated ear mass in different planting arrangements of sweet corn hybrids released between 1933 and 1962 in trials conducted in the 1960s. Nearly all of these authors have observed differences among hybrids in their response to populations. The few studies of sweet corn populations have limited application to contemporary production of processed sweet corn.

Paucity of population research in processing sweet corn reflects: a major gap in agronomic research, is of interest to sweet corn seed and processing industries, and challenges practitioners' ability to make informed crop management decisions. Moreover, addressing this issue would include an economic analysis tailored to the unique aspects of processing sweet corn. Therefore, the objectives were to: (1) quantify the effects of population and commercial hybrid on sweet corn growth, development, ear traits, and yield, (2) determine populations for maximum yield for growers and maximum gross profit margin for processors, and (3) compare populations for maximum yield and maximum gross profit margin to populations observed in processing sweet corn fields in North America.

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0378-4290/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.fcr.2011.12.007

2. Materials and methods

Experiments were conducted in four fields over two years near Urbana, IL, USA (40°6′35″N, 88°12′15″W, 222 m a.s.l.). The previous crop was soybean (*Glycine max* (L.) Merr.). The soil was a Flanagan silt loam (fine, smectitic, mesic Aquic Argiudolls) averaging 3.9% organic matter and a pH of 5.7. Based on soil test recommendations, 129 kg N ha^{-1} (fields 1 and 2) or 140 kg N ha^{-1} (fields 3 and 4) were applied as urea and incorporated with cultivation prior to planting. In temperate regions of North America, processing sweet corn is commonly planted from early-May to late-June; therefore, experiments were conducted across this range of planting dates to more fully represent the variable environmental conditions in which sweet corn is grown. Fields 1, 2, 3, and 4 were planted 12 May 2009, 25 June 2009, 6 May 2010, and 25 June 2010, respectively. Rainfall was supplemented with sprinkler irrigation as needed to ensure crop establishment and avoid crop failure due to drought conditions.

2.1. Experimental approach

The experimental design was a split-plot arrangement within a randomized complete block with five replications. Main plot treatments consisted of six shrunken2 endosperm type sweet corn hybrids commonly used by sweet corn processors (Chip Bahr, Del Monte; Michelle Gardiner, Rogers; Paul Richter, General Mills; Bill Veith, Seneca; pers. com.), including DMC 21-84 (Del Monte), DMC 22-85 (Del Monte), GSS 1477 (Rogers), Magnum II (Rogers), Marvel Edge (Crookham), and Protégé (Rogers). Three-meter wide main plots consisting of four 0.76-m spaced rows were divided into 9.1 m long subplots and assigned one of four populations (43,000, 57,400, 71,700, and 86,000 plants ha^{-1}). Populations were established by seeding the crop at 97,400 seed ha^{-1} and hand-thinning to appropriate populations at 3-collar sweet corn. Populations were counted one week after thinning to confirm intended population treatments were established. Weed control was accomplished by inter-row cultivation, handweeding, and selective herbicides, including atrazine (6-chloro-N̲-ethyl-N̲′-(1-methylethyl)-1,3,5-triazine-2,4-diamine) plus metolachlor (2-chloro-N̲-(2-ethyl-6-methylphenyl)-N̲-(2-methoxy-1-methylethyl)acetamide) applied preemergence.

2.2. Data collection

All data were collected from the center two rows of each subplot. Sweet corn leaf area index (LAI) and photosynthetically active radiation were measured once after silk emergence of all hybrids at three locations in each subplot. Sweet corn LAI was estimated under full-sun conditions within 2 h of solar noon using a linear ceptometer (AccuPAR Linear Ceptometer; Decago Devices, Pullman, WA). Ceptometer measurements of incident light above and below the canopy were used to estimate intercepted photosynthetically active radiation (IPAR). Specifically, IPAR was the plot average of unity minus the fraction of the below-canopy to above-canopy measurements, expressed as a percentage. Sweet corn height, measured from the soil surface to uppermost leaf tip, also was recorded after silk emergence.

Cumulative growing degree days (GDD) were determined beginning with crop planting using a base temperature of 10 °C and daily temperature data from a weather station within 1 km of the experiment location (Illinois State Water Survey, Champaign, IL). 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. Each hybrid was harvested approximately 21 days after mid-silk of the plots assigned 43,000 plants ha^{-1}. Marketable ears, measuring $\geq$4.5 cm in diameter, were hand-harvested over the center 6.1 m length of each plot. Marketable ear number and green ear mass were recorded. Five ears from each subplot were randomly sampled for measurements of ear length and filled ear length. All ears were immediately husked with a husking bed (A&K Development, Eugene, OR) and kernels were removed from the cob with an industry-grade hand-fed corn cutter (A&K Development, Eugene, OR). Husked ear mass and cob mass were recorded. Kernel mass was calculated as the difference in husked mass and cob mass. Recovery was calculated as the percentage of kernel mass represented in the green ear mass sample.

Processing sweet corn is grown under contract, whereby the processor provides seed of specific hybrids and assigns the target population for planting. Growers of processing sweet corn are paid based on the mass of green ears the processor harvests from the field. An economic analysis was conducted to evaluate the processor's gross profit margin in relation to sweet corn population. Gross return was the product of kernel mass yield, kernel mass per case, and wholesale cash price of canned sweet corn. Contract cost was the product of green ear mass yield and grower cash rate. Sweet corn population cost was the product of population and seed cost. Kernel mass per case (6.13 kg $case^{-1}$), wholesale cash price of canned sweet corn ($12 $case^{-1}$), grower cash rate ($110 Mt^{-1}), and seed cost ($3 per 1000 kernels) were obtained from sweet corn seed and processing industries (George Crookham, Crookham Company; Nick George, Midwest Food Processors Association; pers. com.). Gross profit margin to the processor was gross return minus contract cost and population cost.

2.3. Field survey

A survey of 175 sweet corn fields grown for processing was conducted throughout Illinois, Minnesota, and Wisconsin from 2005 to 2007. Some results of this survey have been published previously, including information on weed species persisting management (Williams et al., 2008) and relationships among agronomic traits, environmental conditions, and weed management tactics in sweet corn (Williams et al., 2009). In short, fields were drawn randomly from weekly lists of fields scheduled for harvest by processor-collaborators. Among the response variables collected for each field, crop population prior to harvest also was quantified by processor-collaborators in 110 of the fields.

2.4. Data analysis

To evaluate the significance of hybrid, population, and their interaction on plant height, LAI, IPAR, thermal time to mid-silk, ear length, filled ear length, ear number, green ear mass, husked ear mass, kernel mass, recovery, and gross profit margin, data were analyzed using the Mixed procedure in SAS (2008). Fixed effects included target population and hybrid, along with their interaction, and random effects included field and replicates within a field. Prior to analysis, diagnostic tests of residuals showed data complied with assumptions of homoschedasticity and normality. Where only main effects were significant, hybrid means were compared using protected, Bonferroni-corrected multiple comparisons (Neter et al., 1996), and regression analyses were used to quantify relationships between populations and crop response. When treatment factors and interactions were significant, additional regression analyses were used to quantify relationships between crop responses and populations for each hybrid. Response variables were fitted to linear or quadratic models as a function of observed populations using least-squares regression. Predicted values from regression models were used to identify populations resulting in maximum yield and maximum gross profit margin. Non-overlapping 95% confidence intervals were the basis for identifying differences among hybrids in terms of maximum yield, maximum gross profit margin, and populations associated with maximum responses. Due to lack of normality of survey data, the Kolmogorov–Smirnov test of frequency distributions was used to test the hypothesis that distributions of populations observed in growers' fields were comparable to distributions of populations for maximum yield and maximum gross profit margin in experimental fields. Regression analyses were performed in Sigmaplot 11.0 (SYSTAT Software Inc., Chicago, IL). All hypotheses were tested at $\alpha = 0.05$.

3. Results

3.1. Environmental conditions

Temperature and rainfall patterns among field experiments represent the variable environmental conditions under which sweet corn is grown in temperate North America. Fields 1 and 3 experienced cool temperatures early; generally one-half the cumulative GDDs the first 10 days after planting compared with fields 2 and 4 (data not shown). As a result, time from planting to crop emergence averaged 15 and 5 days for May-planted and June-planted fields, respectively. In addition, timing of rainfall events and total water supply varied by field. Field 1 received 8.3 cm of rainfall within three days of planting and had the highest amount of total water supply for the season at 41.8 cm. In contrast, field 4 received the least amount of water for the season at 22.5 cm. Compared to 30-year means, wet and cool conditions were observed in field 2, whereas dry and hot conditions were observed in field 4.

3.2. Crop growth

Populations altered density of the crop canopy, but not height (Fig. 1A, C, and E). In general, as populations increased from 43,000 to 86,000 plants ha^{-1}, sweet corn added LAI and intercepted more light. For instance, each additional plant m^{-2} added 0.23 (±0.02) m^2 of leaf area, thereby increasing light interception 1.8 (±0.2)%.

The commonly grown commercial hybrids used in this work varied in growth characteristics (Fig. 1B, D, and F). Hybrid DMC 22-85 produced among the densest canopies, averaging 4.3 m^2 m^{-2} of LAI. In contrast, Marvel Edge produced the least dense canopy, averaging 3.4 m^2 m^{-2} of LAI. These differences in LAI affected the plant's ability to intercept light, whereby DMC 22-85 intercepted 6.1% more light than Marvel Edge. Marvel Edge also was among the shortest hybrids, averaging 158 cm, while Magnum II was among the tallest hybrids, averaging 183 cm.

3.3. Crop development

Increases in populations from 43,000 to 86,000 plants ha^{-1} resulted in a subtle, yet significant, delay in crop development. For instance, each additional plant m^{-2} delayed silk emergence 4.7 (±1.3) GDD (Fig. 1G). Under normal conditions in central Illinois, this delay is approximately one-half of a day.

Marvel Edge was the earliest maturing hybrid tested, while DMC 22-85 and Magnum II were the latest maturing hybrids (Fig. 1H). Difference in thermal time to mid-silk of the earliest and latest maturing hybrids was 67 GDD, approximately 5 days.

3.4. Ear traits

Populations affected ear traits important to processing sweet corn (Fig. 1I and K). Filled ear length declined with populations at a rate of 0.49 (±0.05) cm per additional plant m^{-2}; approximately twice the rate of loss compared to overall ear length (data not shown). Recovery also declined with greater populations. As populations increased at a rate of one plant m^{-2}, recovery declined by 0.34 (±0.11)%.

Ear traits also varied among hybrids (Fig. 1J and L). Filled ear length ranged from 16.9 to 18.9 cm and recovery ranged from 32.1 to 37.7% among hybrids. However, filled ear length of hybrids did not appear to be related to their recovery. For instance, while Magnum II produced ears that were filled the longest among hybrids, the hybrid also had the lowest recovery.

3.5. Crop yield

Coefficient of variation in yield data of field 1 was three-fold higher than other fields and may have been in part the result of excessive rainfall and abnormally cool conditions immediately after planting. Highly variable emergence was observed, which creates size hierarchies among neighbors and increases variability in biomass partitioning to the ear (Pagano and Maddonni, 2007; Tollenaar et al., 2006). Therefore, further analysis of yield and yield-derived data (i.e. gross profit margin) focused on fields 2, 3, and 4. Furthermore, responses were similar among the different yield variables; therefore, green ear mass yield will be presented alone for brevity.

Population and hybrid had significant main effects as well as an interactive effect on all measures of crop yield. Based on the quadratic model fit for each hybrid, predicted maximum yield and the population necessary for that maximum yield were identified (Fig. 2). Hybrid DMC 22-85 was among the highest yielding hybrids, with a maximum yield of 19.8 Mt ha^{-1}. In contrast, GSS 1477 was among the lowest yielding hybrids, with a maximum yield of 15.3 Mt ha^{-1}. In terms of population for maximum yield, hybrids were characterized by two groups. Maximum yield of hybrids DMC 21-84, DMC 22-85, Marvel Edge, and Protégé occurred at populations ranging from 60,300 to 70,200 plants ha^{-1}. In contrast, maximum yield of hybrids GSS 1477 and Magnum II occurred at populations ranging from 48,100 to 49,500 plants ha^{-1}. Averaged across hybrids, maximum yield was 17.5 Mt ha^{-1} at a population of 59,100 plants ha^{-1}.

3.6. Gross profit margin

Like crop yield, population and hybrid had significant main effects and an interactive effect on gross profit margin to the processor. Hybrids DMC 22-85 and Marvel Edge had the highest maximum gross profit margins, averaging \$11,600 ha^{-1} (Fig. 3). In contrast, Magnum II and GSS 1477 had the lowest maximum gross profit margin, averaging \$8300 ha^{-1}. Population for maximum gross profit margin among hybrids ranged from 46,500 to 68,100 plants ha^{-1}. Averaged across hybrids, gross profit margin to the processor was \$9900 ha^{-1} at 57,000 plants ha^{-1}.

3.7. Field survey

Of 110 fields of processing sweet corn, the average population was 56,000 plants ha^{-1}, similar to mean population for maximum gross profit margin in field trials (Fig. 4). Indeed, the distribution of populations observed in growers' fields was similar to the distribution of populations for maximum gross profit margin in field trials ($n = 128$, K-S = 0.246, $p = 0.274$). However, growers' fields had lower populations than expected for maximum yield based on field trials ($n = 128$, K-S = 0.375, $p = 0.021$).

4. Discussion

Populations tested in this work influenced sweet corn growth, development, and ear traits. Increasing populations from 43,000 to 86,000 plants ha^{-1} increased sweet corn's ability to capture limited resources such as light. In addition, a delay in thermal time

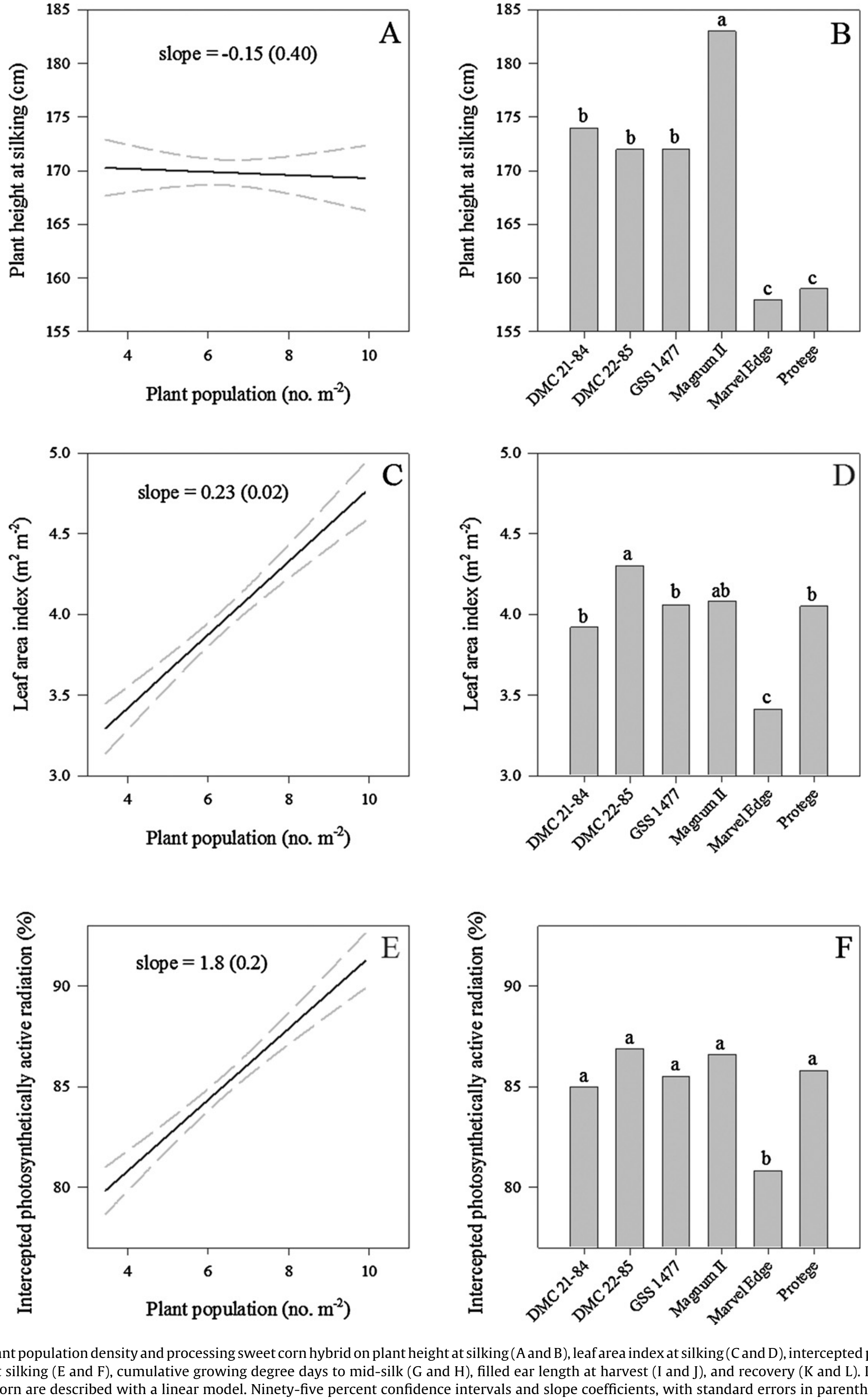

Fig. 1. Effect of plant population density and processing sweet corn hybrid on plant height at silking (A and B), leaf area index at silking (C and D), intercepted photosynthetically active radiation at silking (E and F), cumulative growing degree days to mid-silk (G and H), filled ear length at harvest (I and J), and recovery (K and L). Population density effects on sweet corn are described with a linear model. Ninety-five percent confidence intervals and slope coefficients, with standard errors in parentheses, are reported. Within each trait, hybrids with the same letter are not significantly different based on protected, Bonferroni-corrected multiple comparisons.

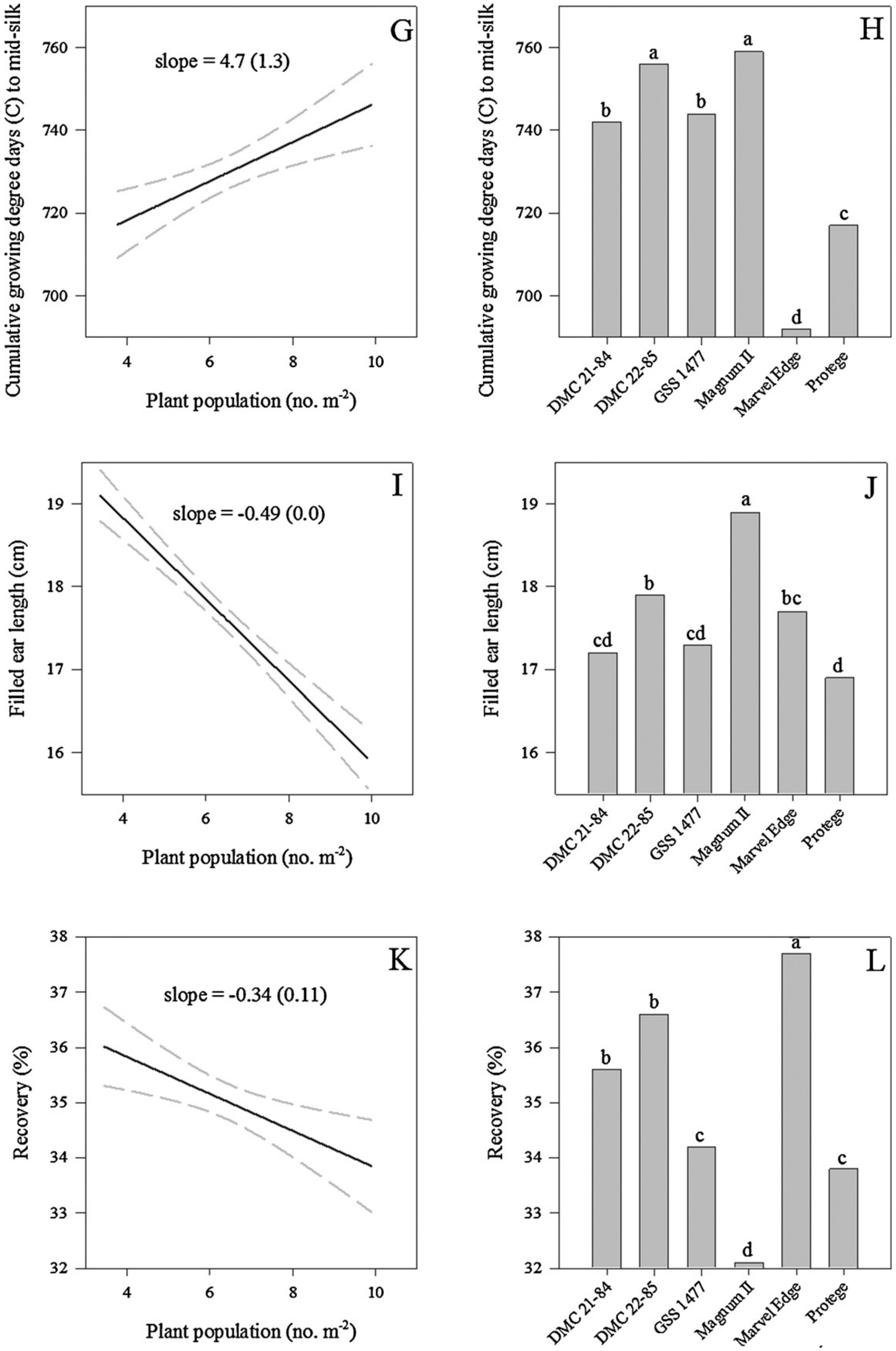

Fig. 1. (*Continued*).

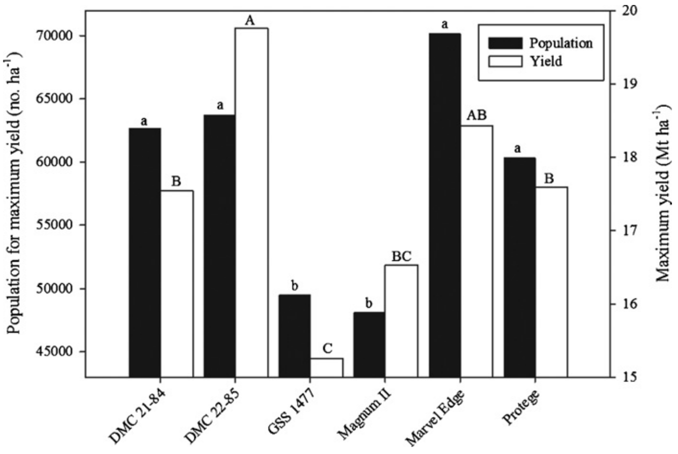

Fig. 2. Plant population density for maximum yield and maximum yield of six processing sweet corn hybrids. Denoted by lower case letters for plant population density and upper case letters for yield, hybrids with the same letter are not significantly different based on non-overlapping 95% confidence intervals.

to mid-silk was observed with increased populations. Developmental delays from interplant competition observed in this work might have agronomic significance when additional plant stresses are involved. For instance, a weed competition-mediated delay in sweet corn silk emergence of 17% corresponded to a 65% yield loss (Williams, 2010). While field corn harvest index response to populations has been well documented (Boomsma et al., 2009; Raymond et al., 2009; Subedi et al., 2006; Tollenaar and Wu, 1999), the extent to which populations affect ear traits important to processing sweet corn is poorly documented. In this work recovery declined linearly with increasing populations, indicating that while yield gains can be realized from higher populations, those higher populations reduce kernel mass as a percentage of total ear mass.

There were notable differences in growth, development, and ear traits among the commonly grown commercial hybrids used in this work. Magnum II was one of the largest, latest-maturing hybrids tested, producing the longest ears; however, it also had the poorest recovery. In contrast, Marvel Edge had one of the smallest canopies and matured early, yet had the highest recovery. A principal factor analysis of 18 phenomorphological traits of 23 sweet corn hybrids showed that a large, late-maturing canopy was the primary factor involved in maintaining sweet corn's ability to tolerate interference from wild-proso millet (*Panicum miliaceum* L.) (So et al., 2009). However, green ear mass was the only yield response variable measured in that work. The present study suggests that hybrids with phenomorphological traits important to weed competitiveness do not necessarily produce ears with traits that are most favorable for processing (i.e. highly recoverable kernel mass).

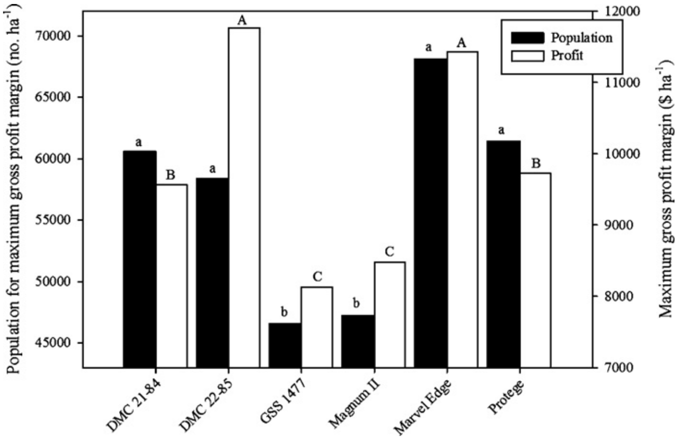

Fig. 3. Plant population density for maximum gross profit margin for the processor and maximum gross profit margin of six processing sweet corn hybrids. Denoted by lower case letters for plant population density and upper case letters for gross profit margin, hybrids with the same letter are not significantly different based on non-overlapping 95% confidence intervals.

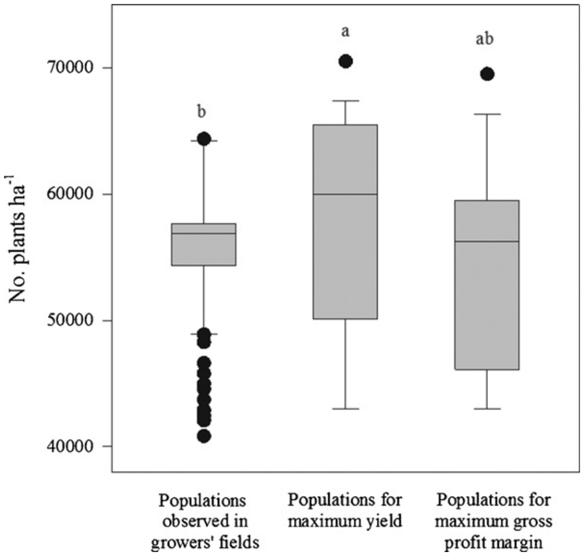

Fig. 4. Distribution of plant population densities observed in growers' fields in North America ($n = 110$) compared to plant population densities for maximum yield ($n = 18$) and plant population densities for maximum gross profit margin for the processor ($n = 18$) based on field experiments. Distributions that are similar are identified with the same letter, based on the Kolmogorov–Smirnov test of frequency distributions.

The processing hybrids used in this study differed not only in yield potential, but also in their ability to tolerate high populations. The highest-yielding hybrids tolerated the highest plant populations. Moreover, tolerance to higher populations did not appear linked to the phenomorphological traits examined in this work. For instance, Magnum II had several growth and developmental similarities to high-yielding DMC 22-85, including the production of long ears; however, yield of Magnum II was among the lowest. In contrast, Marvel Edge produced the smallest, earliest canopy, yet yielded similar to DMC 22-85. Over the last 50 years, yield improvement in field corn is explained in large part by greater stress tolerance, including the crop's ability to yield in high populations (Duvick, 2005; Tollenaar and Wu, 1999). Results of the present study indicate further improvements could be made by breeding for additional tolerance to higher populations in sweet corn.

The economic analysis in this work quantified the significance of processing sweet corn hybrid response to populations. The combination of ear mass yield and recovery takes more accurate stock of hybrid performance than ear number or ear mass alone. As such, the combination of high yield and high recovery in DMC 22-85 and Marvel Edge made them economically superior to all other hybrids tested. Also, the economic impact to processors of changing populations is aided by accounting for both recovery and seed cost. For instance, populations for maximum gross profit margin to the processor were, on average, 2100 plants ha^{-1} lower than population densities for maximum yield. This discrepancy in populations for maximum yield and populations for maximum gross profit margin reflects the decline in recovery, coupled with higher seed costs, as populations increase.

The similarity in the distribution of populations of growers' fields to the distribution of populations for maximum gross profit margin provides validity to the experimental approach used in this work. Sweet corn processors have been making decisions on populations for years, so agreement between these results makes sense, in that processors will require growers to use populations that maximize gross profit margin to the processor. While such a strategy benefits the processor, this approach may compromise grower profit. Our results show higher populations than observed in growers' fields would be needed to maximize ear mass (thereby, grower profit), especially for high-yielding hybrids.

5. Conclusion

Variable populations affected crop growth, development, and yield in plausible ways. Increasing populations from 43,000 to 86,000 plants ha^{-1} linearly increased canopy density, light interception, and length of the vegetative period, while linearly decreasing filled ear length and kernel recovery – a critically important trait in processing sweet corn. A quadratic response described the influence of populations on yield, where yield declined at the highest populations. However, the hybrid itself has a greater apparent impact on yield and recovery than population. Yield and recovery of commercial sweet corn hybrids used in this work, which are also commonly used in processing, varied as much as 4.5 Mt ha^{-1} and 5.6%, respectively. Growing the hybrids at their respective populations to maximize yield would not close the gap in hybrid performance. For instance, in comparing the highest yielding hybrid (Marvel Edge) at its optimal population to the lowest yielding hybrid (Magnum II) at its optimal population, there remains a difference of nearly $3000 ha^{-1} in gross profit margin to the processor.

Optimum populations for field corn in temperate climates have ranged from 79,000 to 84,000 plants ha^{-1} in recent years (Boomsma et al., 2009; Stanger and Lauer, 2006). Such densities exceed populations appropriate for sweet corn. The present study shows that populations for maximum sweet corn yield vary greatly with hybrid, ranging from 48,100 to 70,200 plants ha^{-1}. Differences among commercial hybrids, in maximum yield and populations for maximum yield, suggest tolerance to higher populations in sweet corn could be improved. Moreover, the crop's ability to yield well with high recovery appeared unrelated to plant size, length of vegetative period, or filled ear length.

Sweet corn's ability to perform in higher populations has improved markedly over the last 50 years. In the 1960s, sweet corn was routinely planted at 6000–8000 plants ha^{-1} (Mack, 1972). The recommendation for populations in the 1990s targeted 36,000–43,000 plants ha^{-1} (Ferro et al., 1998). The present research shows that North American growers are using on average 56,000 plants ha^{-1}, which was consistent with populations for optimal gross profit margin. However, both growers and processors could realize increased yield and profit by using certain hybrids at populations higher than currently used.

Acknowledgements

I appreciate the technical assistance of Jim Moody and the many colleagues and students who helped in conducting the field experiments. Aaron Hager provided excellent comments to an earlier draft of the manuscript. I also appreciate discussion with the industry leaders who identified commercial hybrids to use in this work and parameter values for the economic analysis. I thank Crookham Company, Del Monte, and Syngenta Seeds for providing seed. Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Dept. of Agriculture and does not imply its approval to the exclusion of other products or vendors that also may be suitable.

References

Azanza, F., Bar-Zur, A., Juvik, J.A., 1996. Variation in sweet corn kernel characteristics associated with stand establishment and eating quality. Euphytica 87, 7–18.

Boomsma, C.R., Santini, J.B., Tollenaar, M., Vyn, T.J., 2009. Maize morphophysiological responses to intense crowding and low nitrogen availability: an analysis and review. Agron. J. 101, 1426–1452.

Duvick, D.N., 2005. The contribution of breeding to yield advances in maize (*Zea mays* L.). Adv. Agron. 86, 83–145.

Ferro, D.N., Bonanno, A.R., Erhardt, W.H., Wick, R.L., 1998. New England Vegetable Management Guide. Univ. Mass., Office Commun., College Food Natural Resources Publ. AG-1282:10/97.

Mack, H.J., 1972. Effects of population density, plant arrangement, and fertilizers on yield of sweet corn. J. Am. Soc. Hortic. Sci. 97, 757–760.

Morris, T.F., Hamilton, G., Harney, S., 2000. Optimum plant population for fresh-market sweet corn in the northeastern United States. HortTechnology 10, 331–336.

Nafziger, E.D., 1994. Corn planting date and plant-population. J. Prod. Agric. 7, 59–62.

Neter, J., Kutner, M.H., Nachtsheim, C.J., Wasserman, W., 1996. Applied Linear Statistical Models, 4th ed. Irwin, Chicago, IL, p. 1408.

Pagano, E., Maddonni, G.A., 2007. Intra-specific competition in maize: early established hierarchies differ in plant growth and biomass partitioning to the ear around silking. Field Crops Res. 101, 306–320.

Rangarajan, A., Ingall, B., Orfanedes, M., Wolfe, D., 2002. In-row spacing and cultivar affects ear yield and quality of early-planted sweet corn. HortTechnology 12, 410–415.

Raymond, F.D., Alley, M.M., Parrish, D.J., Thomason, W.E., 2009. Plant density and hybrid impacts on corn grain and forage yield and nutrient uptake. J. Plant Nutr. 32, 395–409.

Rogers, I.S., Lomman, G.J., 1988. Effects of plant spacing on yield, size and kernel fill of sweetcorn. Aust. J. Exp. Agric. 28, 787–792.

SAS, 2008. Version 9.2. SAS Institute Inc., Cary, NC.

So, Y.F., Williams, M.M., Pataky, J.K., Davis, A.S., 2009. Principal canopy factors of sweet corn and relationships to competitive ability with wild-proso millet (*Panicum miliaceum*). Weed Sci. 57, 296–303.

Stanger, T.F., Lauer, J.G., 2006. Optimum plant population of bt and non-bt corn in Wisconsin. Agron. J. 98, 914–921.

Subedi, K.D., Ma, B.L., Smith, D.L., 2006. Response of a leafy and non-leafy maize hybrid to population densities and fertilizer nitrogen levels. Crop Sci. 46, 1860–1869.

Tollenaar, M., Deen, W., Echarte, L., Liu, W.D., 2006. Effect of crowding stress on dry matter accumulation and harvest index in maize. Agron. J. 98, 930–937.

Tollenaar, M., Wu, J., 1999. Yield improvement in temperate maize is attributable to greater stress tolerance. Crop Sci. 39, 1597–1604.

Treat, C.L., Tracy, W.F., 1994. Endosperm type effects on biomass production and on stalk and root quality in sweet corn. Crop Sci. 34, 396–399.

Williams, M.M., 2010. Biological significance of low weed population densities on sweet corn. Agron. J. 102, 464–468.

Williams, M.M., Davis, A.S., Rabaey, T.L., Boerboom, C.M., 2009. Linkages among agronomic, environmental and weed management characteristics in North American sweet corn. Field Crops Res. 113, 161–169.

Williams, M.M., Rabaey, T.L., Boerboom, C.M., 2008. Residual weeds of processing sweet corn in the North Central Region. Weed Technol. 22, 646–653.