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Few crop traits accurately predict variables important to productivity of processing sweet corn

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ABSTRACT

Recovery, case production, and gross profit margin, hereafter called ‘processor variables’, are as important metrics to processing sweet corn as grain yield is to field corn production. However, crop traits such as ear number or ear mass alone are reported in sweet corn production research rather than processor variables. The objective of this research was to determine the extent to which certain crop traits could be used to predict variables important to productivity of sweet corn grown for processing. The data used in this research reflected 22 different growing environments over an 8-year period representing 31 processing hybrids. Relations between processor variables and 17 crop traits (5 plant traits, 8 ear traits, and 4 yield traits) were characterized. None of the crop traits adequately predicted recovery, defined as the percentage of green ear mass (i.e. complete ears with husk leaves) represented by fresh kernel mass. Case production, defined as cases of kernels per unit area, was strongly associated ($\rho \geq 0.869$) with ear number, green ear mass, husked ear mass, and fresh kernel mass. Similar correlations ($\rho \geq 0.854$) were found between the yield traits and gross profit margin, defined as the value of case production less the contracted cost of green ear mass. However, regression analyses of relationships between processor variables and individual yield traits showed that fresh kernel mass was by far the best predictor of case production and gross profit margin. While ear number or green ear mass are commonly reported in field research of processing sweet corn, relevancy of the research would be enhanced if fresh kernel mass were measured and reported.

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1. Introduction

Applied research aimed at improving crop productivity is predicated on the ability to accurately measure important crop responses, such as yield, in field tests. Historically for many agronomic crops including field corn (*Zea mays* L.), grain yield at physiological maturity is the primary response variable used to identify superior crop production practices and guide germplasm improvement (Duvick, 2005). Moreover, research equipment has long been available, and is continually improved upon, which aids both public and private researchers in collecting data on grain yield.

Response variables other than grain yield are more important in certain field crops. For instance, sweet corn is not harvested at physiological maturity, but during a narrow window of time at the R3 stage (crop stages defined by Abendroth et al., 2011); approximately 72–76% kernel moisture, depending on endosperm mutation. Furthermore, sweet corn is grown for two markets – fresh market and processing (Tracy, 1993). Fresh market sweet corn for shipping is wholesaled by ear number, such as 50-ear boxes. Processing sweet corn is grown under contract, whereby the processor makes several crop management decisions, including but not limited to hybrid, planting date, and plant population density (Nick George, Midwest Food Processors Association, pers. comm.). Typically, the processor pays the grower a specific rate based on mass of green ears produced per unit area. Therefore, the metric important to the grower of processed sweet corn is green ear mass (i.e. ears with husk leaves), often expressed as Mt ha^{-1}. However, the metric important to the sweet corn processor is cases of kernels (canned or frozen) per contracted field, often expressed as cases ha^{-1}, and hereby referred to as case production.

Throughout the developed world, commercial production of processing sweet corn is extensively mechanized, utilizing self-propelled harvesters and largely automated processing facilities (Brian Maul, Oxbo International, pers. comm.). However, unlike field corn, mechanization of sweet corn harvest and processing in field plot research is rare. Nearly all public and private research programs hand-harvest experimental field plots (author, pers. obs.). Very few public programs, and not all private programs, have the ability to husk green ears or cut fresh kernels from the cob; labor requirements are even higher for those programs with access to

Abbreviations: CGS, crop growth stage; GDD, growing degree day; IPAR, intercepted photosynthetically active radiation; LAI, leaf area index.

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appropriate equipment (namely a husking bed and corn cutter). As such, lack of field plot harvesters, high labor costs, and time constraints at harvest place major limitations on sweet corn research, relative to field corn. For instance, the most recent field research on processing sweet corn does not report case production in studies of plant pathology (Clough et al., 2011), fertility management (Johnson et al., 2012), weed control (Johnson et al., 2010; Williams et al., 2011), and sweet corn breeding and genetics (Assunção et al., 2010; Solomon et al., 2012). Ear number or green ear mass are often the only crop responses reported in research on field productivity of processing sweet corn. Sometimes, other crop responses are reported, including plant traits (e.g. height or canopy density) or ear traits (e.g. ear length or ear width).

There may be a disconnect in the data reported in field research, and the data needed by the seed and processing industries to improve sweet corn production. Ear number is largely insignificant to the processor. Green ear mass does not directly characterize case production. How ear traits relate to sweet corn yield is unreported. Sweet corn processors utilize different variables to help make decisions about field production, hereafter collectively called 'processor variables'. In addition to case production, recovery, defined as the percentage of green ear mass represented by fresh kernel mass, is important. A higher recovery results in less plant material (i.e. primarily husks, cobs, and shanks) going through the processing facility and less waste requiring disposal. Finally, gross profit margin quantifies economic productivity of field operations. Gross profit margin is calculated as the value of case production per unit area less the contracted cost of green ear mass per unit area. In order to directly quantify these processor variables in field research, researchers need to husk ears and cut kernels.

Given the time and cost of measuring fresh kernel mass in field research, is it actually necessary? Perhaps ear number, green ear mass, or a different crop trait, adequately relates to processor variables. Therefore, the objective of this work was to determine the extent to which certain crop traits could be used to predict variables important to productivity of sweet corn grown for processing.

2. Materials and methods

2.1. Data

Data were compiled from previously published field studies on sweet corn (Williams, 2006, 2008, 2009, 2012; Williams et al., 2007, 2008a, 2008b; Williams and Lindquist, 2007; Williams and Masiunas, 2006) and one unpublished study (author, unpublished data). The objectives addressed issues of weed management, interspecific (crop–weed) competition, or intraspecific (crop–crop) competition in sweet corn. All studies measured fresh kernel mass, as well as other crop traits. Collectively, field experiments were conducted in 22 different growing environments over a period of 8 years. A total of 31 processing sweet corn hybrids were evaluated. Seventeen sweet corn plant, ear, and yield traits were identified, although not all traits were reported in every study (Table 1). The compiled dataset had up to 1080 observations of individual crop traits.

The methodological approaches used to grow the crop and characterize traits were largely consistent across studies. All experimental units (i.e. plots) were four 76-cm spaced rows of sweet corn ranging in length of 9.2–12.2 m. Thermal times from emergence or planting to mid-silk (R1 stage) and harvest (R3 stage) were characterized with cumulative growing degree days (GDD) using a base temperature of 10 °C and daily temperature data from a weather station within 1 km of experimental locations. Plant height was measured from the soil surface to the uppermost leaf or plant apex near silking. Also near the time of silking, plant leaf area index (LAI)

Table 1
Summary statistics of 17 sweet corn plant, ear, and yield traits and three crop response variables important to the sweet corn processing industry. Correlations between traits and processor variables are presented, whereby correlations in boldface type are significant at alpha = 0.05.[a]

Type	Trait	Units	CGS	Summary statistics				Processor variable		
				mean	sd	range	*n*	Recovery	Case production	Gross profit margin
								Correlation coefficient		
Plant trait	Thermal time to mid-silk	GDD	R1	729	59	566–950	709	**−0.170**	**−0.128**	**−0.128**
	Thermal time to harvest	GDD	R3	1011	70	898–1202	672	**0.395**	**0.247**	**0.263**
	Plant height	cm	R1	180	23	133–263	856	**−0.707**	**0.116**	**0.108**
	Plant LAI	$m^2\ m^{-2}$	R1	4.26	1.35	1.06–7.92	866	**0.236**	**0.491**	**0.484**
	Plant IPAR	%	R1	85.5	8.8	48.2–98.5	882	**0.093**	**0.374**	**0.361**
Ear trait	Ear number per plant	ears $plant^{-1}$	R3	0.78	0.23	0–1.56	903	**0.235**	**0.679**	**0.661**
	Ear length	cm	R3	19.6	1.6	11.8–24.0	864	0.051	**0.330**	**0.320**
	Filled ear length	cm	R3	17.9	1.9	7.0–23.5	864	**0.085**	**0.410**	**0.397**
	Percent filled length	%	R3	91.1	5.5	48.7–100.0	864	**0.112**	**0.328**	**0.318**
	Row number	-	R3	18.2	0.9	16.4–19.6	79	**0.244**	**0.374**	**0.375**
	Kernel number per row	-	R3	35.5	4.2	26.4–43.6	78	**−0.483**	−0.178	−0.195
	Ear width	mm	R3	41.8	2.0	37.5–47.0	79	**0.615**	**0.755**	**0.763**
	Kernel depth	mm	R3	7.3	1.3	4.9–9.4	79	**0.824**	**0.724**	**0.741**
Yield trait	Ear number	boxes ha^{-1}	R3	961	320	0–1830	1080	**0.394**	**0.869**	**0.854**
	Green ear mass	Mt ha^{-1}	R3	14.58	5.57	0–28.89	1079	**0.430**	**0.952**	**0.937**
	Husked ear mass	Mt ha^{-1}	R3	10.05	4.02	0–18.97	1080	**0.543**	**0.982**	**0.974**
	Fresh kernel mass	Mt ha^{-1}	R3	5.21	2.33	0–11.66	1075	**0.654**	**1.000**	**0.999**
Processor variable	Recovery	%	R3	35.0	5.3	1.5–58.1	1062	**1.000**	–	–
	Case production	cases ha^{-1}	R3	849	379	0–1902	1075	**0.654**	**1.000**	–
	Gross profit margin	\$ ha^{-1}	R3	8604	3969	−1322–20,329	1074	**0.682**	**0.999**	**1.000**

[a] Abbreviations: LAI, leaf area index; IPAR, intercepted photosynthetically active radiation; GDD, growing degree days; CGS, crop growth stage.

and intercepted photosynthetically active radiation (IPAR) were estimated under full sun conditions within two hours of solar noon using a linear ceptometer (AccuPAR Linear Ceptometer; Decagon Devices, Pullman, WA). Sweet corn often was harvested 18–21 days after mid-silk from the center two rows. Marketable ears, measuring ≥4.5 cm in diameter, were hand-harvested over the center 6.1 m length of each plot. Ear number and green ear mass were recorded. Ear number per plant was calculated as the number of harvested ears divided by number of plants within the harvest area. Five to twelve ears were randomly selected from certain plots and measured for ear length, filled ear length, row number, kernel number per row, ear width at midpoint, and kernel depth at midpoint. Percent filled length was calculated as the percent of the ear length with fully developed kernels. Multiple observations of individual ear traits were averaged by plot. All harvested ears were then husked with a husking bed (A&K Development, Eugene, OR) and kernels were cut from the cob using an industry-grade hand-fed corn cutter (A&K Development, Eugene, OR). Husked ear mass and cob mass were recorded. Fresh kernel mass was calculated as the difference in husked mass and cob mass.

Processor variables were characterized for every plot. Recovery was calculated as the percentage of fresh kernel mass represented in green ear mass. Case production was calculated from fresh kernel mass assuming 6.13 kg of kernel mass per case. Gross profit margin to the processor was gross return minus contract cost; whereby gross return was the product of kernel mass yield, kernel mass per case, and wholesale cash price of canned sweet corn (\$12 case^{-1}), and contract cost was the product of green ear mass yield and grower cash rate (\$110 Mt^{-1}). Kernel mass per case, wholesale cash price of canned sweet corn, and grower cash rate were obtained from the sweet corn processing industry (Nick George, Midwest Food Processors Association; pers. com.).

2.2. Data analyses

Pearson correlation analysis between sweet corn traits and processor variables was conducted on the compiled dataset. Probability values for correlations were calculated using the Bonferroni correction at $\alpha = 0.05$ (Neter et al., 1996). Visual inspection was made to identify possible nonlinear relationships. Correlation analysis was performed in SYSTAT 13.0 (SYSTAT Software Inc., Chicago, IL). In some cases, the relationship between a crop trait and a processor variable was nonlinear. For instance, case production does not increase indefinitely with number of ears per plant, since expression of prolificacy (the ability of plants to produce more than one ear per plant) eventually declines as growing conditions become more unfavorable (Hallauer, 1974). Indeed, relationships with a definite 'peak' response were observed between several measures of productivity and ear number per plant. Therefore, regression analysis was used to quantify relationships between ear number per plant and green ear mass, case production, and gross profit margin. Response variables were fitted to the following three-parameter Gaussian model:

$$y = a * \exp^{[-0.5(x - x_o/2)^2]} \quad (1)$$

where a is the maximum predicted response, x_o is the x-value at the maximum predicted response, and b is a shape coefficient. Regression analyses also were used to quantify relationships between sweet corn traits and processor variables with high correlations ($\rho > 0.850$). Processor variables were fitted to linear or quadratic models as a function of crop trait using least-squares regression. Model performance was documented by reporting standard errors of regression coefficients, F-values, and coefficient of determination (R^2) values, or illustrated by plotting observed values against predictions and 95% prediction intervals. Regression analyses were performed in Sigmaplot 11.0 (SYSTAT Software, Inc., Chicago, IL).

3. Results

Summary statistics of crop traits revealed wide diversity in plant phenological and morphological development across the data sets (Table 1). Thermal time to mid-silk ranged from 566 to 950 GDD; an approximately 3-week difference in earliest to latest time to mid-silk. Due in part to length of vegetative period, crop canopy size varied as well. Plant height at mid-silk ranged from 133 to 263 cm. Leaf area indices ranging from 1.06 to 7.92 m^2 m^{-2} resulted in plants with different abilities to intercept light, as evidenced by IPAR values ranging from 48.2 to 98.5%.

Individual ear traits also varied widely (Table 1). Across 903 observations, ear number per plant averaged 0.78, but ranged from 0 to 1.56 ears plant^{-1}. Although ear length varied across the dataset, few ears were completely filled with fully developed kernels, as evidenced by percent filled length response (averaging 91.1%).

Yield traits captured the full range of crop response. Ear number, green ear mass, husked ear mass, and fresh kernel mass ranged from zero, to levels that are outstanding for North American sweet corn production (Table 1). Mean green ear mass observed in the dataset (14.58 Mt ha^{-1}) is nearly identical to mean yields observed in North American processing sweet corn fields (14.40 Mt ha^{-1}) during a similar time period (Williams et al., 2009).

Processor variables also varied widely. Recovery ranged from 1.5 to 58.1%, case production ranged from 0 to 1902 cases ha^{-1}, and gross profit margin ranged from −1322 to 20,329\$ ha^{-1} (Table 1). Mean recovery and gross profit margin observed in the dataset is centered in the range of responses observed for widely used processing hybrids (Williams, 2012).

Recovery was weakly associated with most crop traits (Table 1). At best, a negative association was observed with plant height ($\rho = -0.707$) and a positive association was observed with kernel depth ($\rho = 0.824$). Caution should be exercised when considering correlations between processor variables and row number, kernel number per row, ear width, and kernel depth, as only four environments totaling 78–79 observations were represented.

Case production was weakly associated with plant and ear traits. Although most correlation coefficients were significant, the highest correlation ($\rho = 0.755$) was observed between case production and ear width (Table 1). Similar observations were made between gross profit margin and plant and ear traits.

Although case production and gross profit margin were weakly associated with ear number per plant ($\rho = 0.679$), these relationships were nonlinear. Case production, gross profit margin, and green ear mass were fitted to ear number per plant using Eq. (1). As a result, the maximum predicted response (coefficient a) and ear number per plant at the maximum response (coefficient x_o) were identified (Table 2). In all cases, maximum productivity was predicted near a single ear per plant (0.979–1.010 ears plant^{-1}).

Relatively strong associations were observed between case production and yield traits. Correlation coefficients of 0.869, 0.952, and 0.982 were observed between case production and ear number, green ear mass, and husked ear mass, respectively (Table 1).

Similar to case production, gross profit margin was strongly associated with yield traits, but little else. Correlation coefficients of 0.854, 0.937, 0.974, and 0.999 were observed between case production and ear number, green ear mass, husked ear mass, and fresh kernel mass, respectively (Table 1).

Regression analyses were used to more accurately quantify relationships between case production and yield traits. A quadratic model provided good fit for relationships between case production and ear number, green ear mass, and husked ear mass, as evidenced

Table 2
Regression coefficients and model performance of Eq. (1) for the effect of ear number per plant on green ear mass, case production, and gross profit margin[a].

Dependent variable	a	s.e.	b	s.e.	x_0 (ears plant^{-1})	s.e.	Model performance[b]		
							$F_{(\text{dfn, dfd})}$	$P > F$	R^2
Green ear mass	18.84 Mt ha^{-1}	0.17	0.448	0.014	1.010	0.014	$867_{(2,900)}$	<0.0001	0.658
Case production	1117.2 cases ha^{-1}	13.3	0.399	0.015	0.983	0.014	$549_{(2,895)}$	<0.0001	0.551
Gross profit margin	11,339$ ha^{-1}	131	0.391	0.015	0.979	0.014	$495_{(2,895)}$	<0.0001	0.525

[a] Explanation of model parameters: a is the maximum predicted response, x_0 is the x-value at the maximum predicted response, b is a shape coefficient, and s.e. are standard errors.
[b] Explanation of model performance abbreviations: dfn and dfd = numerator and denominator degrees of freedom, respectively.

by R^2 ranging from 0.756 to 0.967 (Figs. 1A, B, and C). Based on 95% prediction intervals, there was a reduction in variability when case production was predicted from green ear mass rather than ear number. A similar reduction in variability was observed when case production was predicted from husked ear mass rather than green ear mass. The one-to-one relationship with fresh kernel mass is obvious since case production is a linear function of fresh kernel mass (Fig. 1D).

Regression analyses also were used to more accurately quantify relationships between gross profit margin and yield traits. Like case production, a quadratic model provided good fit for relationships between gross profit margin and ear number, green ear mass,

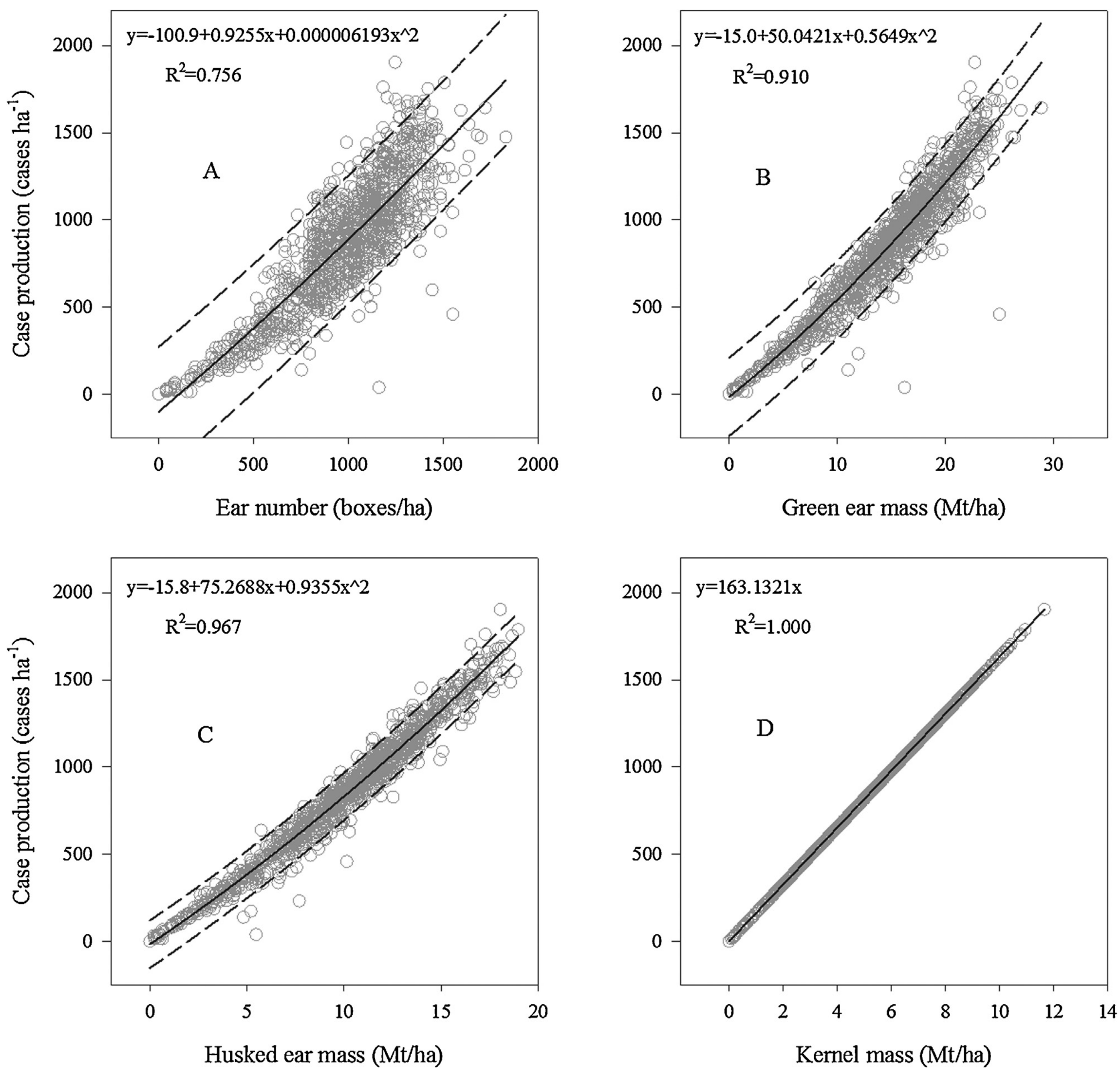

Fig. 1. Relationships between ear number (A), green ear mass (B), husked ear mass (C), or fresh kernel mass (D) and case production. Regression equations, parameter coefficients, R^2 values, predicted response, and 95% prediction intervals are included.

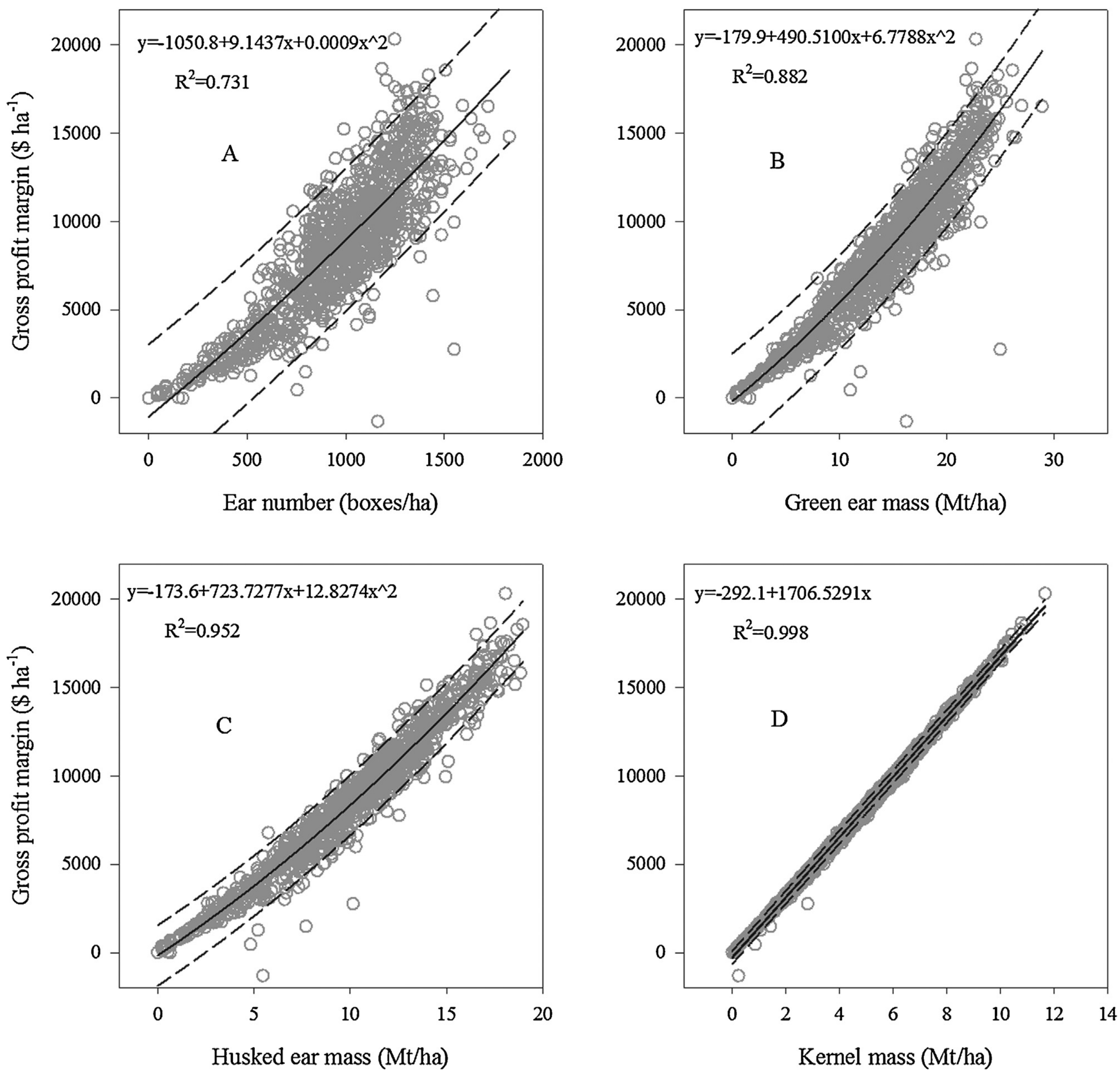

Fig. 2. Relationships between ear number (A), green ear mass (B), husked ear mass (C), or fresh kernel mass (D) and gross profit margin. Regression equations, parameter coefficients, R^2 values, predicted response, and 95% prediction intervals are included.

and husked ear mass (Fig. 2A–C). Similarly, variability between yield traits and gross profit margin were reduced from ear number to green ear mass, and green ear mass to husked ear mass. Furthermore, a linear relationship with fresh kernel mass explained more variability in gross profit margin than other yield traits, as evidenced by $R^2 = 0.998$ (Fig. 2D).

4. Discussion

Weak associations observed between processor variables and most crop traits were not for lack of data. With the exception of four ear traits, associations between processor variables and crop traits were based on 672–1080 observations from as many as 22 different growing environments across an 8-year period. Moreover, crop responses were not confined to narrow range such as average yields, but rather, represented a full span of responses that occur in the field. The wide range in observations of each trait used in this analysis enables a relatively thorough characterization of the relationships between processor variables and reported crop traits. In addition, hybrids in this work represent a majority of the processing sweet corn grown in North America and several hybrids are grown in temperate sweet corn producing regions worldwide.

No crop trait served as an adequate predictor of recovery. The positive association between recovery and kernel depth makes sense, in that taller kernels would likely increase the percentage of ear mass represented by fresh kernel mass. However without additional data, the relationship is not sufficiently robust for crop scientists to rely on kernel depth alone to predict recovery. Recovery appears to be a processor variable that simply must be measured directly.

The practical significance of yield traits as a predictor of case production and gross profit margin can be clarified. Obviously, all four yield traits analyzed in this work can be used to predict case production. However, how much variability is inherent in estimates of case production using each yield trait? To answer this question, regression equations presented earlier were used to identify the

Table 3
Variability in case production and gross profit margin, as represented by 95% prediction intervals (95% PI), when different sweet corn traits are used as the predictor variable. Levels of *x* and *y*, and 95% PIs at *x*, were obtained from regression analyses presented in Figs. 1 and 2.

Dependent variable	Predictor	*x*	*y* (case ha^{-1})	95% PI (case ha^{-1})
Case production	Ear number	1108 boxes ha^{-1}	1000	±368
	Green ear mass	17.0 Mt ha^{-1}	1000	±225
	Husked ear mass	11.8 Mt ha^{-1}	1000	±137
	Kernel mass	6.1 Mt ha^{-1}	1000	±0
Dependent variable	Predictor	*x*	*y* ($ ha^{-1})	95% PI ($ ha^{-1})
Gross profit margin	Ear number	1100 boxes ha^{-1}	10,000	±4108
	Green ear mass	16.9 Mt ha^{-1}	10,000	±2744
	Husked ear mass	11.7 Mt ha^{-1}	10,000	±1764
	Kernel mass	6.1 Mt ha^{-1}	10,000	±414

95% prediction interval around a common level of case production, arbitrarily selected at 1000 cases ha^{-1} (Table 3). In this exercise, 1108 boxes ha^{-1} predicted 1000 ± 368 cases ha^{-1}. Using green ear mass, 17.0 Mt ha^{-1} predicted 1000 ± 225 cases ha^{-1}. Variability in the 1000 cases ha^{-1} estimate was reduced further using husked ear mass (±137 cases ha^{-1}). Essentially, the more a measured yield response physically resembled a case of sweet corn, the more precise the estimate of case production.

How precise is a reported yield trait to the economic reality of processing sweet corn production? Using the same approach described above, variability in an arbitrary gross profit margin estimate of 10,000$ ha^{-1} was compared across yield traits (Table 3). Variability in this estimate (i.e. the 95% prediction interval) dropped approximately one order of magnitude from using ear number as the predictor to using fresh kernel mass (from 4108 $ ha^{-1} and 414 $ ha^{-1}, respectively). Clearly, the 'quality' of processing sweet corn data is not the same across different measures of yield. At a minimum, husked ear mass could be used to improve measurement of crop performance compared to green ear mass. Recognizing the time and cost involved to quantify fresh kernel mass in field research, fresh kernel mass is by far the best at predicting variables important to productivity of processing sweet corn grown.

Ear number per plant is a relatively poor predictor of case production and gross profit margin (ρ = 0.679 and 0.661, respectively); nonetheless, these relationships may shed light on the role of prolificacy in sweet corn. Prolificacy in field corn has been of interest among plant breeders for decades because of positive associations with grain yield (Harris et al., 1976) and tolerance to biotic and abiotic stresses (Anderson et al., 1985; Thomison and Jordan, 1995). Phenotypic expression of multiple ears per plant in prolific field corn lines occurs when growing conditions favor development of subapical ears, such as minimal intraspecific competition (Hallauer, 1974). While both prolific and non-prolific field corn hybrids are commercially available, the extent to which sweet corn breeding programs have selected for or against prolificacy is unclear. Multiple ears per plant are common on some widely used processing sweet corn hybrids when grown at low (<45,000 plants ha^{-1}) plant population densities, but rarely at higher (>60,000 plants ha^{-1}) plant population densities (author, unpublished data). Do subapical ears contribute to maximum productivity in processing sweet corn? Based on regression analysis in the present work, approximately a single ear per plant maximized green ear mass, case production, and gross profit margin. As such, occurrence of subapical ears in sweet corn may indicate the crop is not fully capturing resources available to optimize yield, for instance at low plant population densities. In addition, subapical ears may reduce recovery, as sweet corn cutting equipment is not likely to be calibrated for the small size of subapical ears. While prolificacy may enable sweet corn to partially compensate for poor crop establishment or stand loss, previous work has shown that growers and processors could realize higher yields and profitability by using certain processing sweet corn hybrids at populations higher than currently used (Williams, 2012). In conclusion, the notion of deliberating using low plant populations in favor of prolificacy appears to not maximize sweet corn productivity.

5. Conclusions

While ear number and green ear mass are commonly reported in field research of sweet corn (Assunção et al., 2010; Clough et al., 2011; Johnson et al., 2010, 2012; Solomon et al., 2012; Taylor and Whelan, 2011; Williams et al., 2011), these yield traits are poor predictors of variables important to the processor. Although green ear mass is useful in characterizing contract cost to the processor and returns to the grower, green ear mass is a relatively poor predictor of case production and gross profit margin. The processor makes several decisions that influence profitability for both the grower and processor, including hybrid, planting date, and plant population density. Well-informed decisions regarding these and other crop management factors will be enabled by new, applied research in both private and public sectors. The present work shows that measuring and reporting fresh kernel mass in field research enhances relevancy of the work to the sweet corn processing industry. Conceivably, by reporting results that are useful to the practitioner, novel solutions to difficult production problems more likely would have a positive impact on the industry as a whole.

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