Relationships Among Impurity Components, Sucrose, and Sugarbeet Processing Quality

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ABSTRACT

Sodium, potassium, amino-nitrogen, and invert sugar are naturally-occurring constituents of the sugarbeet root, referred to as impurities, which impede sucrose extraction during routine factory operations. Three germplasm lines selected for low sodium, potassium, or amino-nitrogen and a line selected for high amino-nitrogen concentration from the same parental population and two lines selected from another source, one for high and the other for low amino-nitrogen concentration, were the basis for examining relationships among the impurity components and between the impurity components and sucrose concentration, sucrose loss to molasses, and sucrose extraction rate. Concentrations of the three impurity components were altered through selection; however, in no case did this result in a consistent significant increase in sucrose concentration or estimates of the proportion of the sucrose that would be extracted. Correlation analyses indicated a larger role for sodium than for potassium or amino-nitrogen in determining relative sucrose concentration. Selection for low sodium concentration, however, did not increase the percent extractable sucrose, relative to the parental population. The probability of significant improvement in the processing quality of elite germplasm by reducing the concentration of individual impurity components appears to be low, based upon the populations examined in this study.

Additional Key Words: amino-nitrogen, *Beta vulgaris* L., invert sugar, potassium, recoverable sugar, sodium.

Sugarbeet (*Beta vulgaris* L.) quality is not only contingent on the sucrose concentration of harvested roots but also on the concentration of naturally-occurring soluble constituents of the root, referred to as impurities, that impede the extraction of sucrose during routine factory operations (Campbell, 2002). Each kilogram of impurities prevents the crystallization of 1.5 to 1.8 kg of sucrose that consequently is lost to molasses (Alexander, 1971; Dutton and Huijbregts, 2006). Sugarbeet processors often include some measure of extractable or recoverable sucrose when determining which sugarbeet hybrids growers may plant, and payments to growers are often based upon an estimate of the amount of sucrose that will eventually be marketed as crystallized sugar (Kern, 1998).

Impurities of particular concern to processors include sodium and potassium cations; amino acids, primarily glutamine; and invert sugar, a blend of glucose and fructose (Smith et al., 1977; McGinnis et al., 1982; Campbell, 2002; Dutton and Huijbregts, 2006). Carruthers et al., (1962) and Last and Draycott (1977) demonstrated that the concentrations of sodium, potassium, and amino-nitrogen could be combined to estimate percent sucrose loss to molasses (LTM) or, when combined with sucrose concentration, the concentration of sucrose that will be recovered (recoverable sugar per ton; RST). An alternative method of measuring quality (Dexter, et al., 1967) uses the ratio of sucrose to total dissolved solids (clear juice purity) to calculate an estimate of extractable sugar per ton (ESPT) and the percentage of the total sucrose that will be extracted (PEXT). Although invert sugar negatively impacts processing efficiency, its concentration is seldom considered in assessing processing quality of healthy, recently-harvested roots (Hoffman et al., 2009).

There is little doubt that increases in root yield and sucrose concentration have boosted sugarbeet productivity (Panella et al., 2014). However, improvements in processing quality that have contributed to increased sucrose extraction (Loel et al., 2014) frequently are undervalued. A grower-payment system that rewarded increased recoverable sugar per ton induced management changes by growers, and along with a varietal approval policy that emphasizes recoverable sugar, has benefited American Crystal Sugar Company's growers and shareholders (Hilde et al., 1983; Kern 1988). The extractable sucrose yield of varieties registered in the European Union increased approximately 1.5% per year between 1976 and 2009. Sucrose concentration changed very little over the 33 years; the increase was largely due to an increase in root yield accompanied by a decrease in impurities (Hoffman et al., 2011). Sodium and amino-nitrogen concentrations decreased over the 33 years, but the most notable change was the 30 to 50% decrease in potassium concentration. Thirty to 40% of the decrease in impurities was attributed to breeding progress. Additional examples of progress in reducing impurity concentrations of adapted varieties through applied breeding efforts are cited by Dutton and Huijbregts (2006).

Sodium, potassium, and amino-nitrogen can be shifted substantially with only a few cycles of selection (Powers, et al., 1963; Coe, 1987; Smith and Martin, 1989; Campbell and Fugate, 2012; Campbell and Fugate, 2013), suggesting that additive genetic variance is important in determining the relative levels of these traits (Smith et al., 1973). However, interactions among impurity components, sucrose concentration, and root yield complicate selection for optimum levels of yield and quality traits. In yield trials involving adapted varieties and multiple Red River Valley environments, varietal differences (variety main effects) in sucrose, sodium, potassium, and amino-nitrogen concentration were significant (Campbell and Kern, 1982; Campbell and Kern, 1983). All correlation coefficients among the three impurity components were positive, ranging from 0.24 (sodium -- potassium) to 0.48 (sodium -- amino-nitrogen). Correlation coefficients between sucrose concentration and sodium, potassium, or amino-nitrogen were -0.65, -0.19, and -0.57, respectively (Campbell and Kern, 1983). Schneider et al. (2002) also reported negative relationships between sucrose concentration and the same three impurity components and a positive relationship between potassium and the other two impurity components, but a small negative correlation between sodium and amino-nitrogen. They also located four "ion balance" quantitative trait loci (QTLs) that affected relationships among the impurity components and sucrose concentration. Smith and Martin (1989) observed an increase in extractable sucrose associated with selection for low sodium concentration and Wood et al. (1958) suggested that selecting for high sucrose and low sodium concentration was more effective than selecting for either alone. In contrast, both Finkner and Bauserman (1956) and Powers et al. (1959) concluded that selecting for low sodium concentration was of little or no value in improving processing quality.

Tsialtas and Maslaris (2009) reported genetic variation for selective absorption of potassium over sodium. Positive correlations between selective absorption (as measured by the potassium:sodium ratio) and amino-nitrogen concentration indicated that nitrogen nutrition could be affected by the ability of a variety to exclude sodium from the root. Lindhauer et al., (1990) found that increasing sodium stimulated leaf growth and that sodium was capable of replacing potassium in osmotic functions related to leaf growth, turgidity, and stomata response, to some extent. However, potassium was essential for rapid growth and efficiency of the sink tissue; processes that favor storage root growth and sucrose accumulation. In a British trial (Farley and Draycott, 1974), both sodium and potassium fertilizer increased early-season leaf growth, improved root:top ratio, and increased sucrose concentration. The effect of added sodium on sucrose concentration was progressively smaller when potassium rates were increased, indicating a negative interaction between the two. Although each element increased its own concentration in the root, it proportionally decreased the amino-nitrogen concentration and; therefore, did not affect processing quality.

A better understanding of relationships among the impurity components and between impurity components and sucrose extraction rate could facilitate the development of varieties with improved processing quality. The research summarized in this report examines some of these relationships and the effect of selecting for a single impurity component on sucrose concentration, sucrose loss to molasses, and sucrose extraction rate.

MATERIALS AND METHODS

Nine genotypes including six lines selected almost exclusively for high or low concentrations of sodium, potassium or amino-nitrogen, the two source (parental) populations, CObase and F1010, from which the six lines were selected, and an adapted hybrid, ACH-817 (Crystal Beet Seed, Moorhead, MN) were examined. F1025 (PI 665408), F1026 (PI 665409), and F1027 (PI 665410) were selected for low sodium, potassium, and amino-nitrogen concentrations, respectively, from a common source population (CObase) developed by USDA-ARS, Ft. Collins, CO (Campbell and Fugate, 2012). COhiN is a line selected for high amino-nitrogen concentration from the same Colorado source population. Two lines, one with low (F1028, PI 668026) and one with high amino-nitrogen concentration (F1029, PI 668027), were selected from F1010 (PI 535818), a heterogeneous line with relatively high sucrose concentration (Campbell, 1990; Campbell and Fugate, 2013).

The experimental design for all field evaluations was a randomized complete block with four replicates. Individual experimental units were two-row by 10-m plots with rows 56 cm apart. Trials were planted near Fargo, ND during the first two weeks of May and harvested during the last two weeks of September 2009, 2010, 2011, and 2012. Weeds were controlled with herbicides, cultivation, and hand weeding, as needed. All roots from a single plot were harvested and washed. All measurements were based upon a composite random sample of 10 - 12 roots from each plot.

Each 10- to 12-root sample was processed through a beet saw, the resulting brei sample was mixed, and a portion was quickly frozen for later analysis. Sucrose was determined polarimetrically (Autopol 880, Rudolph Research Analytical, Flanders, NJ) using aluminum sulfate-clarified brei samples (McGinnis, 1982). The aluminum sulfate-clarified filtrate used to determine sucrose concentration also was used to measure sodium, potassium, amino-nitrogen, glucose, and fructose concentrations. Sodium and potassium concentrations were determined by flame-photometry (Corning 410C, Cole-Parmer Instrument Co., Chicago, IL). Amino-nitrogen concentration was determined with a spectrophotometer (Spectronic-21D, Milton Roy Co., Ivyland, PA) using the ICUMAS Copper Method and a wavelength of 610 nm (International Commission for Uniform Methods of Sugar Analysis, 2007). Aliquots of an L-(+) – glutamine solution were used to establish a standard curve. The sucrose loss-to-molasses (LTM) was based upon Car-

ruthers-Oldfield-Teague (1962) equations as modified by American Crystal Sugar Co. (Moorhead, MN) to calculate payments to individual growers: LTM = {[(Na x 3.5) + (K x 2.5) + (amino-N x 9.5)] / 1100} x 1.5, with the impurities expressed in ppm and LTM as g kg^{-1}. The loss to molasses was subtracted from the sucrose concentration to obtain the recoverable sucrose concentration. The impurity index is the ratio of a weighted sum of the sodium, potassium, and amino-nitrogen concentrations, [(Na x 3.5) + (K x 2.5) + (amino-N x 9.5)], to the sucrose concentration (Reichman et al., 1977). Extractable sucrose concentration was determined using polarimetry (Autopol 880 with purity option, Rudolph Research Analytical) to measure sucrose concentration and refractometry (J57 Automatic Refractometer, Rudolph Research Analytical) to measure total dissolved solids (Dexter et al., 1967). Percent extractable sucrose was calculated by dividing extractable sucrose concentration by total sucrose concentration (Dexter et al., 1967). Dry matter was the oven-dried (80°C) weight of a brei sample after 72 h divided by its fresh weight (~20 g), expressed as g kg^{-1}. Glucose and fructose concentrations were determined colorimetrically using end point, enzyme-coupled assays (Spackman and Cobb, 2001; Klotz and Martins, 2007). Invert sugar concentration was the sum of the glucose and fructose concentrations. Invert sugar was not measured in 2009. The concentrations of all variables are reported on a fresh weight basis.

The SAS GLM procedure (ver. 9.4, SAS Institute, Inc., Cary, NC) was used for the analysis of variance. Years were assumed to be random effects and genotypes fixed effects (McIntosh, 1983). Fisher's Protected LSD was used to determine when differences among means were significant (P=0.05). Each year the SAS CORR procedure was used to calculate Pearson's correlation coefficients (r) for pairs of independent variables of interest. The 3- or 4-year means of these correlation coefficients were calculated using a z-transformation, averaging the values of z for each pair of variables, and converting the average z back to an r value (Snedecor and Cochran, 1967). The commercial hybrid, ACH-817, was included as a reference variety in the analysis of variance but was not included in the calculation of the correlation coefficients. The "estimate" function of the SAS GLM procedure was used to quantify differences between each selected genotype and its parental population and between the high and low amino-nitrogen selections. Portions of the data presented in this report were the basis for publications documenting the development and characteristics of the lines included in this report (Campbell and Fugate, 2012; Campbell and Fugate, 2013).

RESULTS

The sodium concentration of F1025 (Table 1) was consistently lower than the sodium concentration of the population from which it was derived (COBase). Based upon the four-year means, the sodium concen-

tration of F1025 was reduced by one-third, compared to the parental population, as a result of selection for low sodium. There was no clear indication that selection for amino-nitrogen concentration or low potassium concentration had altered the sodium concentration in either of the two populations subjected to selection (CObase or F1010).

Selection for low potassium (F1026) reduced the potassium concentration by 24%, compared to the parental population. Selection for low amino-nitrogen concentration was accompanied by a 10% increase in the potassium concentration of F1027, compared to CObase, and a 13% increase in F1028, compared to F1010. Selection for low sodium concentration (F1025) or high amino-nitrogen concentration (COhiN and F1029) had no apparent effect on potassium concentration.

The amino-nitrogen concentration of F1028 was 68% of the concentration of F1010; in contrast, the amino-nitrogen concentration of F1029 was 1.6 times the concentration of F1010 and 2.4 times the concentration of F1028. The difference between the amino-nitrogen concentration of F1027 and the population from which it was selected (CObase) was not significant; however, the amino-nitrogen concentration of COhiN was 1.6 times that of the parental population (CObase) and 1.8 times the concentration of F1027.

With two exceptions, the changes in the concentration of each of the three individual impurity components (sodium, potassium, or amino-nitrogen) resulting from selection had no, or only a minor impact on sucrose loss to molasses (Table 1), a measure based solely on the concentration of sodium, potassium, and amino-nitrogen. Selecting for high amino-nitrogen concentration resulted in a 26% increase in the loss to molasses of COhiN and a 28% increase in F1029, compared to their respective parental populations. The potassium: sodium ratio of F1025, the low-sodium line, was 1.3 times that of its parental population (CObase) and 1.5 times that of F1026, the low potassium line (Table 1). The potassium: sodium ratio of F1026 was 0.8 times the potassium: sodium ratio of CObase. Selecting for either high or low amino-nitrogen concentration did not have a detectable impact on the potassium: sodium ratio.

F1010 and the two lines selected from F1010, F1028 and F1029, had higher sucrose concentrations than CObase or the four lines selected from CObase (Table 2). Selection for high or low impurity concentrations did not alter the sucrose concentration in either of the populations evaluated. In general, differences in sucrose concentration means were a reflection of relative dry matter concentration means (Fig. 1D) (Pack, 1930; Tsialtas and Maslaris, 2009). Selecting for individual impurity components did not alter dry matter concentration. As a consequence of the increased loss to molasses and absence of an accompanying decrease in sucrose concentration associated with the two lines selected for high amino-nitrogen, F1029 and COhiN were the only lines that had lower recoverable sucrose concentrations than their respective parental populations (Table 2).

Low impurity concentrations and/or high sucrose concentrations

Table 1. Sodium, potassium, and amino-nitrogen concentration, loss to molasses, and the potassium:sodium ratio of lines selected for individual impurity components, the respective parental populations, and an adapted hybrid in field trials at Fargo, ND, 2009-2012.

	Year				
Genotype	**2009**	**2010**	**2011**	**2012**	**Mean**
			Sodium, ppm		
F1025	**450 a***	**300 a**	**647 c**	**395 a**	**448 C**
F1026	530 a	385 a	805 bc	550 a	568 AB
F1027	755 a	360 a	947 a-c	535 a	649 A
COhiN	695 a	395 a	1102 ab	465 a	664 AB
CObase	695 a	400 a	1090 ab	465 a	662 A
F1028	785 a	310 a	1165 a	430 a	672 A
F1029	430 a	300 a	912 a-c	495 a	534 BC
F1010	515 a	300 a	1010 ab	530 a	589 AB
A-817	575 a	440 a	822 bc	440 a	569 AB
Mean	603 B	354 C	945 A	478 BC	595
			Potassium, ppm		
F1025	1620 a	2140 a	2115 a-c	2260 c	2034 CD
F1026	**1245 b**	**1445 a**	**1900 c**	**1915 d**	**1626 E**
F1027	1830 a	2410 a	2380 a	2785 a	2351 A
COhiN	1675 a	2415 a	2315 ab	2375 bc	2195 A-C
Cobase	1825 a	2145 a	2160 a-c	2405 bc	2134 B-D
F1028	1835 a	2145 a	2340 ab	2665 ab	2246 AB
F1029	1670 a	2040 a	2075 bc	2480 bc	2066 B-D
F1010	1620 a	1925 a	2160 a-c	2245 c	1987 D
A-817	1735 a	2090 a	1905 c	2340 c	2017 CD
Mean	1672 C	2084 B	2150 B	2386 A	2073
			Amino-nitrogen, ppm		
F1025	648 bc	603 ab	479 bc	1387 ab	779 BC
F1026	767 b	427 bc	520 bc	837 c	638 CD
F1027	**473 cd**	**433 bc**	**322 c**	**816 c**	**511 DE**
COhiN	**838 ab**	**831 a**	**830 a**	**1100 bc**	**900 AB**
Cobase	533 cd	438 bc	413 bc	829 c	553 DE
F1028	**412 d**	**264 c**	**288 c**	**680 c**	**411 E**
F1029	**1040 a**	**487 bc**	**633 ab**	**1802 a**	**991 A**
F1010	527 cd	362 bc	484 bc	1057 bc	607 D
A-817	511 cd	373 bc	627 ab	1040 bc	638 CD
Mean	639 B	468 B	511 B	1061 A	670

Table 1 *(Continued).* Sodium, potassium, and amino-nitrogen concentration, loss to molasses, and the potassium:sodium ratio of lines selected for individual impurity components, the respective parental populations, and an adapted hybrid in field trials at Fargo, ND, 2009-2012.

	Year				
Genotype	**2009**	**2010**	**2011**	**2012**	**Mean**
			Loss to molasses, g kg^{-1}		
F1025	16.0 c	18.9 ab	16.5 b	27.6 ab	19.8 B
F1026	16.7 bc	12.3 c	17.1 b	20.0 c	16.5 C
F1027	16.0 c	15.5 a-c	17.4 b	22.6 bc	17.9 BC
COhiN	19.9 ab	20.9 a	23.9 a	24.6 bc	22.3 A
Cobase	16.4 bc	14.9 bc	17.9 b	21.2 bc	17.6 BC
F1028	15.3 c	12.2 c	17.3 b	20.0 c	16.2 C
F1029	21.2 a	14.7 bc	19.6 b	34.2 a	22.4 A
F1010	14.8 c	12.7 c	18.5 b	23.9 bc	17.5 BC
A-817	15.3 c	14.1 bc	18.5 b	23.6 bc	17.9 BC
Mean	16.8 BC	15.1 C	18.5 B	24.2 A	18.7
			Potassium:sodium		
F1025	4.20 a	7.09 a	3.34 a	5.83 ab	5.12 A
F1026	2.72 a	3.73 a	2.47 a	4.14 c	3.27 C
F1027	2.48 a	6.70 a	2.53 a	5.32 a-c	4.26 B
COhiN	2.58 a	6.23 a	2.25 a	5.37 a-c	4.11 B
Cobase	2.93 a	5.89 a	2.06 a	5.40 a-c	4.07 BC
F1028	2.47 a	6.96 a	2.36 a	6.23 a	4.50 AB
F1029	4.20 a	6.96 a	2.28 a	5.09 a-c	4.63 AB
F1010	3.34 a	6.65 a	2.17 a	4.46 bc	4.16 B
A-817	3.34 a	5.12 a	2.50 a	5.32 a-c	4.07 BC
Mean	3.14 C	6.15 A	2.44 D	5.24 B	4.24

* Differences among genotypes within a year followed by the same lower case letter are not significant, according to Fisher's protected $LSD_{0.05}$; differences among main effect means followed by the same upper case letter are not significant (P = 0.05).

will result in low impurity indices, an indicator of improved processing quality. Selecting for low concentrations of sodium, potassium, or amino-nitrogen did not result in a significant reduction in the impurity index (Table 2). However, the combination of increased amino-nitrogen and the minimal effect of selection for high amino-nitrogen on sucrose concentration resulted in relatively high impurity indices for COhiN and F1029.

Table 2. Sucrose, dry matter, impurity index, recoverable sucrose, extractable sucrose concentration, and the percent extraction of lines selected for individual impurity components, the corresponding parental populations, and an adapted hybrid in field trials at Fargo, ND, 2009-2012.

	Year				
Genotype	**2009**	**2010**	**2011**	**2012**	**Mean**
			Sucrose, g kg^{-1}		
F1025	142 Cd*	139 e	131 bc	187 b	149 C
F1026	139 d	137 e	130 bc	173 cd	145 CD
F1027	135 d	146 c-e	131 bc	180 b-d	148 C
COhiN	133 d	140 de	123 c	171 d	142 D
CObase	140 d	140 de	125 c	176 cd	145 CD
F1028	151 bc	152 b-d	131 bc	189 b	155 B
F1029	151 bc	156 a-c	135 b	182 bc	156 B
F1010	155 b	164 ab	139 b	177 cd	158 B
A-817	165 a	167 a	151 a	202 a	171 A
Mean	146 B	149 B	132 C	182 A	152
			Dry matter, g kg^{-1}		
F1025	221 bc	177 d	158 a	262 a	205 B-D
F1026	220 bc	191 b-d	153 a	241 a	210 CD
F1027	210 de	213 a	149 a	239 a	203 B-D
COhiN	208 e	177 d	138 a	236 a	190 E
Cobase	219 b-d	186 cd	147 a	230 a	196 DE
F1028	215 c-e	207 ab	150 a	247 a	205 B-D
F1029	231 a	205 a-c	157 a	257 a	213 AB
F1010	228 ab	214 a	163 a	239 a	211 A-C
A-817	235 a	212 a	163 a	252 a	215 A
Mean	221 B	198 C	153 D	245 A	204
			Impurity index†		
F1025	85.6 bc	91.0 ab	94.6 b	112.8 ab	96.0 BC
F1026	91.2 a-c	66.7 bc	98.9 b	88.4 b	86.3 C-E
F1027	88.4 bc	79.5 bc	95.6 b	94.6 b	89.5 C-E
COhiN	113.2 a	112.2 a	146.5 a	109.1 ab	120.2 A
Cobase	88.9 bc	80.6 bc	107.9 b	91.3 b	92.2 CD
F1028	75.7 c	60.3 c	100.6 b	79.4 b	79.0 DE
F1029	107.4 ab	70.6 bc	108.7 b	143.2 a	107.5 AB
F1010	72.2 c	58.0 c	99.1 b	102.2 b	82.9 C-E
A-817	70.4 c	63.4 c	92.3 b	87.9 b	78.5 E
Mean	88.1 BC	75.8 C	104.9 A	101.0 AB	92.5

Table 2 *(Continued).* Sucrose, dry matter, impurity index, recoverable sucrose, extractable sucrose concentration, and the percent extraction of lines selected for individual impurity components, the corresponding parental populations, and an adapted hybrid in field trials at Fargo, ND, 2009-2012.

	Year				
Genotype	**2009**	**2010**	**2011**	**2012**	**Mean**
			Recoverable sucrose, kg Mg^{-1}		
F1025	126 cd	118 d	114 bc	159 bc	29 D
F1026	122 de	126 b-d	112 bc	153 c	128 D
F1027	119 de	130 b-d	113 bc	157 bc	130 D
COhiN	113 e	119 d	98 d	146 c	119 E
CObase	124 de	125 cd	106 cd	155 bc	127 D
F1028	136 b-d	139 a-c	113 bc	168 ab	139 BC
F1029	130 bc	141 ab	115 bc	148 c	133 CD
F1010	140 ab	151 a	120 b	153 c	141 B
A-817	150 a	153 a	132 a	178 a	153 A
Mean	129 B	134 B	114 C	157 A	133
			Extractable sucrose, kg Mg^{-1}		
F1025	119 cd	110 d	109 bc	157 bc	124 C
F1026	117 de	116 d	104 b-d	146 cd	121 CD
F1027	108 f	120 b-d	105 b-d	154 b-d	122 C
COhiN	111 ef	112 d	97 d	145 d	116 D
Cobase	116 d-f	116 cd	101 cd	151 cd	121 CD
F1028	126 bc	129 a-c	106 b-d	162 b	131 B
F1029	127 bc	131 ab	110 bc	154 b-d	130 B
F1010	131 b	141 a	112 b	149 cd	133 B
A-817	141 a	141 a	126 a	175 a	146 A
Mean	122 B	124 B	107 C	155 A	127
			Extractable percent‡		
F1025	84.0 ab	80.6 cd	83.1 a	84.2 a	82.9 B-D
F1026	84.3 ab	83.4 a-c	80.5 a	84.4 a	83.1 BC
F1027	80.0 c	82.4 b-d	80.2 a	85.6 a	82.1 CD
COhiN	83.1 ab	79.8 d	78.9 a	84.8 a	81.7 D
Cobase	82.8 b	82.7 b-d	80.5 a	85.7 a	82.9 B-D
F1028	83.4 ab	84.8 ab	81.2 a	86.0 a	83.9 AB
F1029	84.0 ab	83.8 ab	81.3 a	84.9 a	83.5 AB
F1010	84.7 ab	85.9 a	79.9 a	84.1 a	83.7 AB
A-817	85.4 a	84.3 ab	83.2 a	86.6 a	84.9 A
Mean	83.5 B	83.1 B	81.0 C	85.1 A	83.2

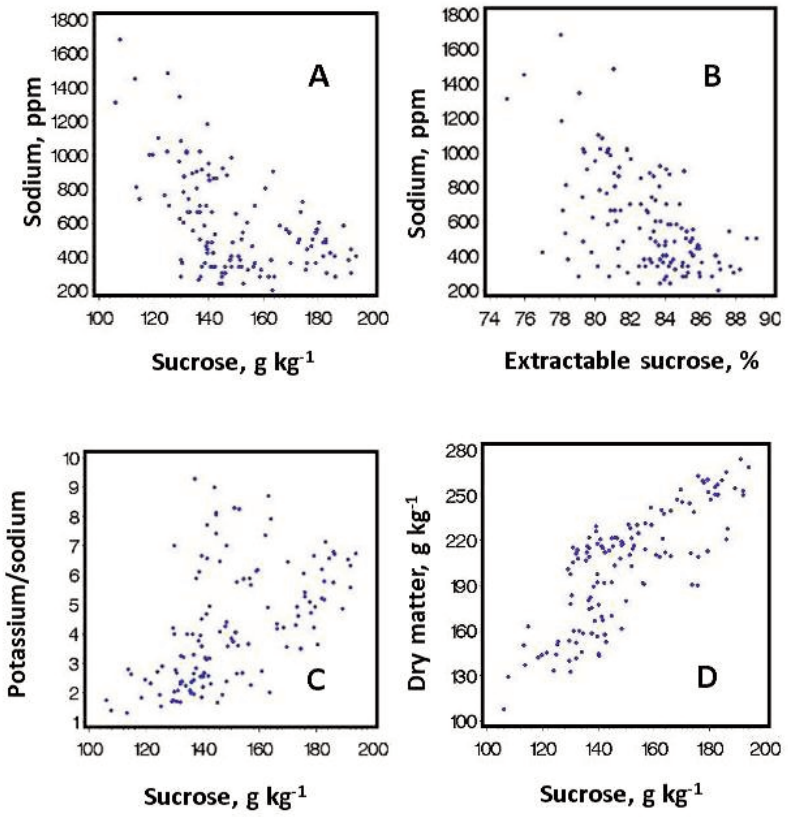
* Differences among genotypes within a year followed by the same lower case letter are not significant, according to Fisher's protected $LSD_{0.05}$; differences among main effect means followed by the same upper case letter are not significant (P = 0.05).
† Impurity Index = [(Na x 3.5) + (K x 2.5) + (amino-N x 9.5)] / sucrose.
‡ Extraction percent = (Extractable sucrose / sucrose) x 100.

Table 3. Glucose, fructose, and invert sugar concentration of lines selected for individual impurity components, the corresponding parental populations, and an adapted hybrid in field trials at Fargo, ND, 2010-2012.

	Year			
Genotype	**2010**	**2011**	**2012**	**Mean**
		Glucose, mg g^{-1}		
F1025	3.86 a*	1.89 b	0.80 a	2.18 B
F1026	4.71 a	3.88 a	1.41 a	3.34 A
F1027	4.31 a	2.12 b	0.99 a	2.48 B
COhiN	4.38 a	1.67 b	0.94 a	2.33 B
CObase	3.41 a	2.28 b	0.77 a	2.15 B
F1028	2.96 a	2.24 b	1.03 a	2.08 B
F1029	3.57 a	1.71 b	0.99 a	2.09 B
F1010	3.20 a	1.64 b	0.82 a	1.88 B
A-817	3.44 a	1.39 b	1.29 a	2.04 B
Mean	3.76 A	2.09 B	1.00 C	2.28
		Fructose, mg g^{-1}		
F1025	2.04 c	1.36 a	0.96 a	1.45 A
F1026	2.51 bc	2.17 a	0.89 a	1.86 A
F1027	2.95 ab	1.14 a	0.90 a	1.66 A
COhiN	3.66 a	0.49 a	0.85 a	1.67 A
Cobase	2.43 bc	0.86 a	0.95 a	1.41 A
F1028	3.01 ab	0.82 a	1.56 a	1.80 A
F1029	2.22 bc	1.26 a	0.57 a	1.35 A
F1010	2.07 c	0.55 a	1.02 a	1.22 A
A-817	2.02 c	0.90 a	1.50 a	1.47 A
Mean	2.55 A	1.06 B	1.02 B	1.54
		Invert sugar, mg g^{-1}		
F1025	5.89 b	3.25 b	1.77 a	3.64 BC
F1026	7.24 b	6.05 a	2.30 a	5.20 A
F1027	7.27 ab	3.26 b	1.89 a	4.14 B
COhiN	8.04 a	2.15 b	1.80 a	4.00 BC
Cobase	5.84 b	3.14 b	1.72 a	3.56 BC
F1028	5.97 b	3.06 b	2.59 a	3.88 BC
F1029	5.79 b	2.97 b	1.55 a	3.44 BC
F1010	5.27 b	2.19 b	1.84 a	3.10 C
A-817	5.45 b	2.29 b	2.79 a	3.51 BC
Mean	6.31 A	3.15 B	2.03 C	3.83

* Differences among genotypes within a year followed by the same lower case letter are not significant, according to Fisher's protected $LSD_{0.05}$; differences among main effect means followed by the same upper case letter are not significant (P = 0.05).

Figure 1. Relationships between sodium and sucrose concentration (A), percent extractable sucrose (extractable sucrose / total sucrose) and sodium (B), potassium:sodium ratio and sucrose concentration (C), and sucrose and dry matter concentration (D) in roots of six sugarbeet lines selected for either high or low sodium, potassium, or amino-nitrogen concentration and their two source populations, in field trials near Fargo, ND, 2009-2012 (n = 128; 8 genotypes X 4 years X 4 replicates/year).



F1010 and the two lines selected from F1010 (F1028 and F1029) had higher extractable sucrose concentrations than CObase and the four lines selected from CObase (Table 2). However, altering individual impurity concentrations through selection did not affect extractable sucrose concentration, an indicator of processing quality that does not include sodium, potassium, or amino-nitrogen concentration in its calculation. Hence, it follows that extraction percent, the ratio of extractable sucrose concentration to sucrose concentration, was more

closely related to the source population than to differences in sucrose and extractable sucrose concentrations associated with selection for the individual impurity components.

The only indication that altering sodium, potassium, or amino-nitrogen concentration affected invert sugar concentration was the relatively high concentrations of glucose and invert sugar in F1026, the line selected for low potassium concentration (Table 3). Differences among within year comparisons were not always significant; however, F1026 had the highest glucose concentration in all three years, the highest fructose concentration in 2011, and the highest invert sugar concentration in 2011. The average glucose and invert sugar concentration of F1026 was approximately 1.5 times the corresponding concentrations of CObase.

Forty-two of the 152 within-year correlation coefficients between pairs of variables were significant at or above the 95% probability level and an additional eight were significant at the 90% level (Table 4). Twenty-four of the 50 significant correlations occurred in 2010 with the remaining 26 approximately equally distributed over the other three years. The correlation coefficients for only four variable-pairs were significant in all four years (Table 4 and Fig. 1); two additional variable–pairs were significant in 2009, 2010, and 2011. Sodium concentration was one of the variables in three of these six pairs of variables and the potassium-sodium ratio was included in one. The only other traits included among the six pairs of variables with consistently significant correlation coefficients were sucrose concentration, dry matter concentration, and extraction percent.

The negative correlations between sodium and sucrose concentration (Fig. 1A), and the association between an increase in dry matter with an increase in sucrose concentration (Fig. 1D) and a decrease in sodium concentration, indicates that relationships among these three traits were not solely due to adding or deleting water with the relative constituents of the dry matter remaining constant (Table 4). The relatively strong negative association between sodium and sucrose concentration and the absence of a significant relationship between potassium and sucrose concentration suggests that increasing the potassium-sodium ratio by reducing the sodium concentration would be more effective than increasing the relative potassium concentration in increasing sucrose concentration.

The absence of a significant shift in loss to molasses in response to selection for low sodium (F1025), potassium (F1026), or amino-nitrogen (F1028), compared to their parental populations (Table 1), suggests that a shift in one impurity component is compensated for by a shift in one or both of the other impurity components. However, correlations among the three traits were low (Table 4). The positive correlation between sodium and potassium had the highest average correlation (0.21) but was not significant in any of the four years. Correlations between sodium and amino-nitrogen were significant in 2010 and 2012, and between potassium and amino-nitrogen in 2010, but

Table 4. Correlation coefficients for pairs of variables involving impurity components and measures of sugarbeet processing quality, based upon observations from trials conducted at Fargo, ND, 2009 – 2012.

Traits	2009	2010	2011	2012	Average
SUC - DM‡	0.69 **	0.56 **	0.65 **	0.42 *	0.59
Na - PEXT	-0.58 **	-0.47 **	-0.57 **	-0.42 *	-0.51
K/Na-SUC	0.46 **	0.30 *	0.48 **	0.68 **	0.49
Na - SUC	-0.45 **	-0.35 *	-0.51 **	-0.58 **	-0.48
Na - DM	-0.57 **	-0.45 **	-0.49 **	-0.22	-0.44
LTM-PEXT	-0.09	-0.83 **	-0.26	-0.26	-0.42
DM - PEXT	0.43 **	0.57 **	0.48 **	0.04	0.39
K/Na - DM	0.52 **	0.25	0.50 **	0.12	0.36
PEXT - INV	.	-0.47 **	-0.02	-0.34 †	-0.29
K-PEXT	-0.42 **	-0.59 **	0.03	-0.02	-0.27
SUC - GLU	.	-0.43 *	-0.07	-0.24	-0.25
AMN -PEXT	0.19	-0.74 **	-0.04	-0.23	-0.25
LTM - SUC	-0.32 †	-0.40 *	0.05	-0.26	-0.24
PES - GLU	.	-0.42 *	-0.06	-0.21	-0.24
SUC - INV	.	-0.38 *	0.00	-0.27	-0.22
Na - K	0.18	0.29	0.23	0.12	0.21
PEXT- FRU	.	-0.34 †	0.02	-0.26	-0.20
LTM - DM	-0.20	-0.52 **	-0.03	0.07	-0.18
AMN - SUC	-0.21	-0.42 *	0.22	-0.25	-0.17
Na - FRU	.	0.30 †	-0.10	0.24	0.15
K/Na - GLU	.	-0.17	0.08	-0.31 *	-0.14
K -GLU	.	-0.06	-0.23	-0.10	-0.13
Na - INV	.	0.21	-0.15	0.31 †	0.13
K/Na - INV	.	-0.12	0.06	-0.30 †	-0.12
K - DM	-0.13	-0.12	-0.05	-0.18	-0.12
K - FRU	.	0.34 †	-0.19	0.17	0.11
AMN - INV	.	0.38 *	-0.06	-0.01	0.11
K - SUC	0.12	-0.02	0.09	0.23	0.11
Na - AMN	-0.19	0.35 *	-0.07	0.31 †	0.11
AMN - GLU	.	0.35 *	-0.10	0.05	0.10
LTM - FRU	.	0.28	-0.04	0.02	0.09
AMN - DM	0.00	-0.59 **	0.20	0.13	-0.09
DM - FRU	.	-0.06	-0.08	-0.11	-0.08
SUC - FRU	.	-0.14	0.07	-0.17	-0.08
AMN - FRU	.	0.26	0.00	-0.03	0.08
DM - INV	.	-0.15	-0.01	-0.06	-0.07
LTM - INV	.	0.29	-0.15	0.04	0.06
K/Na-AMN	0.14	-0.01	0.01	-0.36 *	-0.06
K - GLU	.	0.10	-0.14	0.20	0.05
K/Na - FRU	.	0.01	0.03	-0.17	-0.04
LTM - GLU	.	0.22	-0.20	0.05	0.02
K - INV	.	0.11	-0.26	0.12	-0.01
DM - GLU	.	-0.17	0.07	0.08	-0.01
K - AMN	-0.28	0.38 *	-0.13	0.01	0.00

‡ Abbreviations: AMN = amino-nitrogen; DM = dry matter; FRU = fructose; GLU = glucose; INV = invert sugar; K = potassium; K/Na = potassium-sodium ratio; LTM = loss to molasses; Na = sodium; PEXT = percent extractable sucrose; SUC = sucrose.

†, *, and ** indicate a correlation coefficient differs significantly from zero at the 0.10, 0.05, and 0.01 probability level, respectively.

Table 5. Spearman's rank correlations comparing year-to-year consistency of the relative importance of pairs of variables in Table 4.

	Year			4-year
Year	**2010**	**2011**	**2012**	**Average**
		r_s		
2009	0.52 *	0.79 **	0.65 **	0.84 **
2010	- - -	0.12	0.63 **	0.89 **
2011	- - -	- - -	0.19	0.35 *
2012	- - -	- - -	- - -	0.82 **

* and ** indicate correlation coefficient differs significantly from zero at the 0.05 and 0.01 probability level, respectively.

both had very low average correlations; 0.11 and 0.00, respectively. A negative correlation between the potassium-sodium ratio and amino-nitrogen concentration was significant in 2012 only and had average correlation of -0.06.

Spearman's rank correlations (Table 5) provided an indication of the year-to-year consistency in the relative importance of pairs of variables (Table 4). The relatively high correlations involving 2009 may be due, in part, to the absence of correlations that included invert sugar, glucose, and fructose concentrations in 2009 (Table 4). Because the yearly correlations are components of the four-year average correlation, correlations between a year and the average would be expected to be relatively high and generally positive. Correlations of 2009, 2010, and 2012 with the four-year average were from 2.3 to 2.5 times the correlation between 2011 and the four-year average (Table 5). This and the relatively low correlations between 2010 and 2011 and between 2011 and 2012 indicate that environment influences associations among quality components and their relationship to some measures of processing quality (Campbell and Kern, 1982).

DISCUSSION AND CONCLUSIONS

Concentrations of three impurity components were altered through selection; however, in no case did this result in a consistent significant increase in sucrose concentration (Table 2) or the proportion of the sucrose that is likely to be extracted (Table 6). Smith (1988) reported similar results with lines related to some of the lines used in this trial when grown in a different environment. In general, the positive correlations among sodium, potassium, and amino-nitrogen noted in some reports (Campbell and Kern, 1983; Powers et al., 1959) were not readily apparent in these trials. Both of the lines selected for low amino-ni-

Table 6. Differences in some common measures of sugarbeet processing quality between lines selected for sodium, potassium, or amino-nitrogen concentration and their respective parental populations and differences between lines selected for low and high amino-nitrogen from a common parental population, based upon 2009 – 2012 trials at Fargo, ND.

Differences	Loss to molasses	Impurity index	Recoverable sugar	Extractable sugar	Percent extractable
	g kg^{-1}		--------- *kg Mg^{-1}* ---------		*%*
F1025 - CObase	2.16 †	38.1	1.69	3.00	0.02
F1026 - CObase	-1.08	-58.7	0.84	-0.09	0.23
F1027 - CObase	0.29	-26.4	2.44	0.94	-0.85
COhiN -CObase	4.70 **	280.5 **	-8.31 *	-4.84 †	-1.25
COhiN - F1027	4.41 **	306.9 **	-10.75 **	-5.78 *	-0.39
F1028 - F1010	-1.26	-39.0	-1.62	-1.88	0.21
F1029 - F1010	4.97 **	245.9 **	-7.5 *	-2.41	-0.16
F1029 - F1028	6.23 **	284.9 **	-5.88 †	-0.53	-0.38

†, *, and ** indicate the absolute value of the difference is greater than zero at the 0.10, 0.05, and 0.01 probability level, respectively.

trogen concentration, F1027 and F1028, had relatively high potassium concentrations and the line selected for low sodium concentration, F1025, had a relatively low amino-nitrogen concentration (Table 1). The significant contrasts between COhiN and F1029 and their respective parental populations (CObase and F1010) and their corresponding low amino-nitrogen lines, F1027 and F1028, (Table 6) confirm that amino-nitrogen concentration has a significant role in determining processing quality. However, the absence of a clear relationship between the reduced amino-nitrogen concentration of F1027 or F1028 and increased sucrose concentration or enhanced processing quality (Table 6) suggests that it may be difficult to noticeably enhance quality by selecting for reduced amino-nitrogen concentration within elite breeding populations. The only indication that selecting for low impurity concentration affected invert sugar concentration was the relatively high fructose and invert sugar concentrations associated with F1026 (Table 3), the line selected for low potassium concentration.

The negative correlation between sodium and sucrose concentration (Table 4 and Fig. 1A) is consistent with other reports (Wood et al., 1958; Smith and Martin, 1989). Increased sodium also appeared to be associated with decreased dry matter and a reduction in sucrose extraction percent (Fig. 1B). The absence of significant correlations be-

tween sodium and potassium and between potassium and sucrose suggest that the positive correlation between the potassium-sodium ratio and sucrose concentration (Figure 1C) is predominantly determined by sodium concentration, and to a lesser extent, potassium concentration. Most of the dry matter of sugarbeet roots is sucrose and sucrose concentration is reported on a fresh-weight basis; hence the strong positive correlations between dry matter and sucrose concentration (Fig. 1D) are expected. It follows that the negative correlation between sucrose and sodium may contribute to the negative correlation between sodium and dry matter.

The correlation analyses indicated a larger role for sodium than for potassium or amino-nitrogen in determining relative sucrose concentration. However, two estimates of the quantity of sugar that will be available for marketing (RST and EST) and improvements in three measures of processing quality were not significant in the line selected for low sodium (F1025), compared to the parental population (Table 6). The possible relationship between reduced potassium and elevated invert sugar concentrations needs confirmation and further examination, if reoccurring. The probability of significant improvement in the processing quality of elite germplasm by reducing the concentration of individual impurity components is low, based upon the populations examined in this study.

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LITERATURE CITED

Alexander, J.T. 1971. Factors affecting quality. p 371-381. *In* R.T. Johnson, J.T. Alexander, G.E. Rush, and G.R. Hawkes (eds.) Advances in Sugarbeet Production: Principles and Practices. Iowa State Univ. Press, Ames, Iowa.

Campbell, L.G. 1990. Registration of F1010 sugarbeet germplasm. Crop Sci. 30: 429-430.

Campbell, L.G. 2002. Sugar beet quality improvement. J. Crop Prod. 5: 395-413.

Campbell, L.G., and K.K. Fugate. 2012. Registration of F1025, F1026, and F1027 sugarbeet genetic stocks with low concentrations of sodium, potassium, or amino-nitrogen. J. Plant Reg. 7: 250-256.

Campbell, L.G. and K.K. Fugate. 2013. Divergent selection for amino-nitrogen concentration in sugarbeet roots. J Sugar Beet Res. 50(3): 1-13.

Campbell, L.G. and J.J. Kern. 1982. Genotype X environment interactions in sugarbeet yield trials. Crop Sci. 22: 932-935.

Campbell, L.G. and J.J. Kern. 1983. Relationships among components of yield and quality of sugarbeets. J. Am. Soc. Sugar Beet Technol. 22: 135-145.

Carruthers, A., J.F.T. Oldfield, and H.J. Teague. 1962. Assessment of beet quality. 15th Tech. Conf., British Sugar Corp. 28p.

Coe. G.E. 1987. Selecting sugar beets for low content of nonsucrose solubles. J Am. Soc. Sugar Beet Technol. 24: 41-48.

Dexter, S.T., M.G. Frakes, and F.W. Snyder. 1967. A rapid and practical method of determining extractable white sugar as may be applied to the evaluation of agronomic practices and grower deliveries in the sugar beet industry. J. Am. Soc. Sugar Beet Technol. 14: 433-454.

Dutton, J., and T. Huijbregts. 2006. Root quality and processing. p. 409-442. *In* A.P. Draycott (ed.), Sugar Beet, Blackwell Publishing Ltd., Oxford, UK.

Farley, R.F., and A.P. Draycott. 1974. Growth and yield of sugar beet in relation to potassium and sodium supply. J. Sci. Food Agric. 26: 385-392.

Finkner, R.E., and H. M. Bauserman. 1956. Breeding sugar beets with reference to sodium, sucrose, and raffinose content. J. Am. Soc. Sugar Beet Technol. 9: 170-177.

Hilde, D.J., S. Bass, R.W. Levos, and R.L. Ellingson. 1983. Grower practices system promotes beet quality in the Red River Valley. J. Am. Soc. Sugar Beet Technol. 22: 73-88.

Hoffman, C.M., T. Huijbregts, N. van Swaaij, and R. Jansen. 2009. Impact of different environments in Europe on yield and quality of sugar beet genotypes. Europ. J. Agron. 30: 17-26.

Hoffman, C.M., J. Loel, C. Kenter, and B. Maerlaender. 2011. Analysis of the breeding progress in sugarbeet. In Proc. 36th Biennial Meeting of Am. Soc. Sugar Beet Technol., Albuquerque, NM, 2 – 5 March 2011. http://assbt-proceedings.org.

International Commission on Uniform Methods of Sugar Analysis. 2007. Method GS6-5, Determination of α-amino nitrogen by the copper method ('Blue number'). Verlag Dr. Albert Bartens, KG, Berlin.

Kern, J.J. 1988. The effects of American Crystal's variety approval system on sugarbeet production and income in the Red River Valley. 1987 Sugarbeet Research and Extension Reports. Coop. Ext. Serv. North Dakota State Univ., Fargo, ND 18: 186-193.

Klotz, K.L., and D.N. Martins. 2007. Microplate assay for rapid determination of sucrose, glucose, fructose, and raffinose. J. Sugar Beet Res. 44: 169-170.

Last, P.J., and A.P. Draycott. 1977. Relationships between clarified beet juice purity and easily measured impurities. Int. Sugar J. 79: 183-185.

Lindhauer, M.G., H.E. Haeder, and H. Beringer. 1990. Osmotic potentials and solute concentrations in sugar beet plants cultivated with varying potassium/sodium ratios. Z. Planzenernähr. Bodenk. 153:25-32.

Loel, J., C. Kenter, B. Märländer, C. Hoffman. 2014. Assessment of breeding progress in sugar beet by testing old and new varieties under greenhouse and field conditions. Europ. J. Agron. 52: 146-156.

McGinnis, R.A. 1982. Analysis of sucrose content. p. 67-76. *In* R.A. McGinnis (ed.) Beet Sugar Technology, 3rd ed. Beet Sugar Dev. Foundation, Denver, CO.

McGinnis, R.A., R.M. Sequeira, and J. Dedek. 1982. Chemistry of the beet and processing materials. p. 25-63. *In* R.A. McGinnis (ed.) Beet Sugar Technology, 3rd ed. Beet Sugar Dev. Foundation, Denver, CO.

McIntosh, M.S. 1983. Analysis of combined experiments. Agron. J. 75: 153-155.

Pack, D.A. 1930. Selection characters as correlated with percentage of sucrose, weight, and sucrose content of sugar beets. J. Ag. Res. 40: 523-546.

Panella, L., S.R. Kaffka, R.T. Lewellen, J.M. McGrath, M.S. Metzger, and C.A. Strausbaugh. 2014. Sugarbeet. p 357-395. *In* S. Smith, B. Diers, J. Specht, and B. Carver (eds.) Yield Gains in Major U.S. Field Crops. CSSA Special Publication 33. CSSA, Madison, WI.

Powers, L., R.F. Finkner, G.E. Rush, R.R. Wood, and D. F. Peterson. 1959. Genetic improvement of processing quality in sugar beets. J. Am. Soc. Sugar Beet Technol. 10: 578-593.

Powers, L., W.R. Schmehl, W.T. Federer, and M.G. Payne. 1963. Chemical, genetic, and soils studies involving thirteen characters in sugar beet. J. Am. Soc. Sugar Beet Technol. 12: 393-448.

Reichman, G.A., E.J. Doering, L.C. Benz, and R.F. Follett. 1977. Effects of water-table depth and irrigation on sugarbeet yield and quality. J. Am. Soc. Sugar Beet Technol. 19:275-287.

Schneider, K., R. Schafer-Pregl, D.C. Borchardt, and F. Salamini. 2002. Mapping QTLs for sucrose content, yield, and quality in a sugar beet population fingerprinted by EST-related markers. Theor. Appl. Genet. 104: 1107-1113.

Smith, G.A. 1988. Effects of plant breeding on sugarbeet composition. *In* M.A. Clarke and M.A. Godshall (ed.). Chemistry and Processing of Sugarbeet and Sugarcane. Elsevier Science Publishers, Amsterdam, the Netherlands. p. 9-19.

Smith, G.A., R.J. Hecker, G.W. Maag, and D.M. Rasmuson. 1973. Combining ability and gene action in an eight parent diallel cross of sugar beet. Crop Sci. 13: 312-316.

Smith, G.A., and S.S. Martin. 1989. Effect of selection for sugar beet purity components on quality and extraction. Crop Sci. 29: 294-298.

Smith, G.A., S.S. Martin, and K.A. Ash. 1977. Path coefficient analysis of sugar beet purity components. Crop Sci. 17:249-253.

Snedecor, G.W., and W.G. Cochran. 1967. Statistical Methods 6th Ed. Iowa State Univ. Press, Ames, Iowa.

Spackman, V.M.T., and A.H. Cobb. 2001. An enzyme-based method for the rapid determination of sucrose, glucose, and fructose in sugar beet roots and the effects of impact damage and postharvest storage in clamps. J. Sci. Food Agric. 82: 80-86.

Tsialtas, J.T., and N. Maslaris. 2009. Selective absorption of K over Na in sugar beet cultivars and its relationship with yield and quality in two contrasting environments of central Greece. J. Agron. Crop Sci. 195: 384-392.

Wood, R.R., H.L. Bush, and R.K. Oldemeyer. 1958. The sucrose-sodium relationship in selecting sugar beets. J. Am. Soc. Sugar Beet Technol. 10: 133-137.