Root Yield and Quality of Sugarbeet Hybrids with Pollinators Selected for Sodium, Potassium, or Amino-nitrogen Concentration

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ABSTRACT

Sodium, potassium, and amino-nitrogen, referred to as impurities, are constituents of sugarbeet that impede sucrose extraction. Lines selected for low or high concentration of a single impurity component were crossed with a common female line to determine their impact on the sodium, potassium, amino-nitrogen, sucrose, recoverable sucrose, and invert sugar concentration and root yield in the resulting hybrids. The relatively low sodium and potassium concentration of hybrids with low-sodium and low-potassium pollinators, respectively, indicated that pollinators with relatively low sodium or potassium concentration can substantially reduce the sodium or potassium concentration of a hybrid. Roots of hybrids with pollinators selected for high amino-nitrogen concentration had higher amino-nitrogen concentrations than hybrids with their unselected parental populations as pollinators. However, the difference between the reduced amino-nitrogen concentration observed for hybrids with pollinators selected for low amino-nitrogen concentration and the amino-nitrogen concentration of hybrids with the unselected parental population as a pollinator was not significant. In general, altering one of the impurity components resulted in only small changes in root yield, sucrose concentration, or loss-to-molasses. Selection for a combination of impurity components, sucrose concentration, and root yield traits and multi-environment evaluations will be required to improve the value and productivity of the crop.

Additional Key Words: *Beta vulgaris* L., invert sugar, loss to molasses, recoverable sugar, sucrose.

Some naturally occurring soluble constituents, collectively referred to as impurities, of sugarbeet (*Beta vulgaris* L.) roots impede the extraction of sucrose during normal factory operations. Each kilogram of these 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; Carlson, 2007). Impurities of particular concern to processors include sodium and potassium cations, amino acids, 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). 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; Vermeulen, 2015).

As a result of the combined efforts of plant breeders, processors, and growers, reductions in the sucrose loss to molasses that have enhanced processing efficiency have occurred simultaneously with increased root yields and moderate increases in sucrose concentration. A 1.5% annual increase in the extractable sucrose yield of varieties registered in the European Union between 1976 and 2009 was largely due to an increase in root yield accompanied by a decrease in impurities with little change in sucrose concentration. Thirty to 40% of the decrease in impurities was attributed to breeding progress (Hoffman et al., 2011). A varietal approval policy that emphasized recoverable sugar motivated commercial breeders to increase their focus on sucrose concentration and processing quality. This, along with a payment system that rewards growers for increased recoverable sugar per ton, has benefited American Crystal Sugar Company's growers and shareholders (Hilde et al., 1983; Kern, 1988). Additional examples of progress in reducing impurity concentrations of adapted varieties through applied breeding efforts are cited by Dutton and Huijbregts (2006).

Selection primarily for low concentrations of sodium, potassium, or amino-nitrogen has produced lines with substantially lower concentrations than the concentrations of these impurities in the populations from which they were selected (Campbell and Fugate, 2012; 2013). Selection for high amino-nitrogen concentration also culminated in lines with significantly higher amino-nitrogen concentration than their unselected parental populations (Campbell and Fugate, 2013; 2015). This report examines the influence of lines with relatively low sodium, potassium, or amino-nitrogen and relatively high amino-nitrogen concentration on the concentration of these impurities, sucrose and invert sugar concentration, and root yield of hybrids when crossed as pollinators with a common female parent. Also included are hybrids with the two source populations as pollinators. The performance of hybrids with the selected lines as pollinators is compared to the performance of hybrids with their unselected source populations as pollinators.

MATERIALS AND METHODS

Ten sugarbeet hybrids were evaluated in trials near Fargo, ND in 2012 and 2014. The pollinators for six of the hybrids were lines selected for a single impurity component (sodium, potassium, or amino-nitrogen) from two broad-based populations, CObase and F1010 (PI 535818). CObase is a population formed by pollinating cytoplasmic-male-sterile (cms) plants from a monogerm Cercospora leaf spot (CLS; caused by *Cercospora beticola* Sacc.) and curly top (caused by *Beet curly top virus*) resistant breeding line with pollen from plants selected for CLS resistance and high sucrose concentration from a multigerm heterogeneous population (Smith and Martin, 1989). F1010 is a high-sucrose heterogeneous germplasm selected from a broad-based population formed by intermating selected accessions from the USDA-ARS *Beta* germplasm collection (Campbell, 1990). F1025 (PI 665408), F1026 (PI 665409), and F1027 (PI 665410) are lines with low sodium, potassium, and amino-nitrogen concentrations, respectively, selected from CObase (Campbell and Fugate, 2012). F1028 (PI 668026) is a low amino-nitrogen line selected from F1010 (Campbell and Fugate, 2013). F1029 (PI 668027) and COhiN are lines with high amino-nitrogen concentrations selected from F1010 and CObase, respectively. The six lines selected for the individual impurity components and the two parental (unselected) populations were crossed as pollinators with a common cms line, L53cms (PI 590842). L53, a line developed by USDA-ARS, Logan, UT, is noted for its high general combining ability for root yield and sucrose concentration (Theurer, 1978). Two adapted hybrids, Triton (Seedex, Fargo, ND) and ACH-R716 (Crystal Beet Seed. Moorhead, MN), also were included in the trials as reference hybrids.

The trials were planted 2 May 2012 and 22 May 2014 and harvested 21 September 2012 and 1 October 2014. Each experimental unit (plot) consisted of two 10-m rows with a 56 cm row-spacing. The trials were managed for optimal yield and quality. Weeds were controlled with herbicides, cultivation, and hand weeding. Root yield was the fresh weight of all roots harvested from a single plot converted to Mg ha^{-1}. The sucrose concentrations and quality variables used in the analyses were an average of two composite random samples comprised of 10 – 12 roots from each plot. The experimental design was a randomized complete block with three replicates per year. 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 hybrids fixed effects (McIntosh, 1983). The least significant difference (LSD) was used to determine when differences among means were significant (= 0.05). Each year the SAS CORR procedure was used to calculate Pearson's correlation coefficients

(r) for pairs of independent variables of interest (n = 30).

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 (International Commission for Uniform Methods of Sugar Analysis, 2007). The sucrose loss to molasses (LTM) was based upon Carruthers-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. Dry matter was the oven-dried (80 C) weight of a brei sample divided by its fresh weight (~20 g). Glucose and fructose concentrations were determined colorimetrically using end point, enzyme-coupled assays (Klotz and Martins, 2007). Invert sugar concentration was the sum of the glucose and fructose concentrations. The concentrations of all variables are reported on a fresh weight basis.

RESULTS

The average sodium concentration of the hybrid with the low-sodium pollinator, L53 cms / F1025, was 667 ppm, 73% of the 918 ppm of the hybrid with the unselected parental population as the pollinator, L53 cms / CObase (Table 1). Average differences between the potassium and amino nitrogen concentrations of L53 cms / F1025 and L53 cms / CObase were small and not significant. The average potassium concentration of the hybrid with the low-potassium pollinator, L53 cms / F1026, was 478 ppm less than the hybrid with the unselected population as the pollinator, L53 cms / CObase, and all other hybrids with pollinators selected from CObase except for the hybrid with the high amino-nitrogen selection as the pollinator, L53 cms / COhiN. Average differences between the sodium and amino-nitrogen concentrations of L53 cms / F1026 and L53 cms / CObase were not significant. The average amino-nitrogen concentration of the hybrid with the high amino-nitrogen pollinator selected from CObase, L53 cms / COhiN, was 1.5 times the concentration of the hybrid with the unselected parental population as the pollinator, L53 cms / CObase, and 1.6 times the concentration of the hybrid with the low amino-nitrogen selection from the same source population, L53 cms / F1027. However, the 42 ppm difference between L53cms / F1027 and L53 cms / CObase was not significant. A similar pattern occurred when the high and low amino-nitrogen selections from F1010 were used as polli-

Table 1. Sodium, potassium, and amino-nitrogen concentration and loss to molasses of hybrids of lines selected for high or low concentration of a single impurity component and their unselected parental populations as pollinators with a common cytoplasmic male sterile (CMS) parent, and two adapted hybrid cultivars, Fargo, ND, 2012 and 2014.

CMS / Pollinator	2012		2014		Mean		2012		2014		Mean	
	Sodium, ppm						Potassium, ppm					
L53 / CObase	483	bc†	1353	ab	918	A	2317	b	2053	bc	2185	B
L53 / F1025	**403**	**c**	**930**	**c**	**667**	**C**	2080	bd	2090	a-c	2085	B-D
L53 / F1026	546	bc	1386	ab	967	AB	**1777**	**e**	**1637**	**d**	**1707**	**E**
L53 / F1027	533	bc	1547	ab	1040	AB	2293	bc	2005	b-d	2149	BC
L53 / COhiN	540	bc	1170	bc	855	BC	2063	b-e	1806	cd	1935	C-E
L53 / F1010	496	bc	1340	ab	918	B	1963	de	1903	b-d	1933	C-E
L53 / F1028	476	bc	1513	ab	995	AB	1980	de	2290	ab	2135	BC
L53 / F1029	473	bc	1383	ab	928	B	2023	c-e	1750	cd	1888	DE
Triton	640	ab	1306	ab	973	AB	2306	bc	2068	a-c	2196	B
ACH-R761	717	a	1580	a	1148	A	2677	a	2460	a	2568	A
Mean	531	A	1351	B	941		2148	A	2008	B	2078	
	Amino-nitrogen, ppm						Loss to molasses, g kg^{-1}					
L53 / CObase	708	ab	698	cd	703	C	19	a-c	22	b-d	21	B-D
L53 / F1025	762	ab	756	cd	759	C	19	a-c	21	cd	20	D
L53 / F1026	892	ab	798	c	845	BC	20	a-c	22	b-d	21	B-D
L53 / F1027	**545**	**b**	**776**	**cd**	**661**	**C**	17	bc	24	b-d	21	CD
L53 / COhiN	**1112**	**a**	**993**	**b**	**1052**	**AB**	24	a	25	bc	24	A-C
L53 / F1010	917	ab	644	d	781	C	21	a-c	21	cd	21	B-D
L53 / F1028	**596**	**b**	**691**	**cd**	**643**	**C**	16	c	24	b-d	20	D
L53 / F1029	**1100**	**a**	**1251**	**a**	**1176**	**A**	23	ab	29	a	26	A
Triton	911	ab	739	cd	712	C	21	a-c	22	cd	21	B-D
ACH-R761	753	ab	671	cd	787	C	23	ab	25	b	24	AB
Mean	822	A	802	A	812		21	B	24	A	22	

†Differences among hybrids within a year followed by the same lowercase letter are not significant based upon $LSD_{0.05}$; differences among main effects followed by the same uppercase letter are not significant ($P = 0.05$).

Table 2. Potassium:sodium ratio, root yield, and sucrose, recoverable sucrose, invert sugar and dry matter concentration of hybrids of lines selected for high or low concentration of a single impurity component and their unselected parental populations as pollinators with a common cytoplasmic male sterile (CMS) parent, and two adapted hybrid cultivars, Fargo, ND, 2012 and 2014.

CMS / Pollinator	2012	2014	Mean	2012	2014	Mean
	Potassium:sodium, ratio			Sucrose, g kg^{-1}		
L53 / CObase	4.8 ab†	1.5 b	3.2 AB	179 b-d	127 b	153 D
L53 / F1025	5.1 a	2.3 a	3.7 A	182 b-d	135 ab	158 A-D
L53 / F1026	3.3 c	1.2 b	2.2 C	179 b-d	132 ab	156 B-D
L53 / F1027	4.4 a-c	1.3 b	2.8 BC	189 a	130 ab	159 A-C
L53 / COhiN	4.1 a-c	1.6 b	2.8 BC	177 cd	132 ab	155 CD
L53 / F1010	3.9 a-c	1.5 b	2.7 BC	184 ab	137 ab	160 A-C
L53 / F1028	4.2 a-c	1.6 b	2.9 BC	182 b-d	130 ab	156 B-D
L53 / F1029	4.6 a-c	1.3 b	2.9 BC	189 a	139 a	164 A
Triton	3.6 bc	1.6 b	2.6 BC	183 a-c	139 a	161 AB
ACH-R761	3.9 a-c	1.6 b	2.7 BC	176 d	128 ab	152 D
Mean	4.2 A	1.5 B	2.9	182 A	133 B	158
	Recoverable sucrose, kg Mg^{-1}			Root yield, Mg ha^{-1}		
L53 / CObase	160 bc	104 bc	132 A-C	52.7 ab	41.8 bc	47.3 BC
L53 / F1025	162 a-c	114 a-c	138 A	42.0 b	42.2 bc	42.1 C
L53 / F1026	159 bc	109 a-c	134 A-C	47.5 ab	44.4 b	46.0 BC
L53 / F1027	171 a	105 a-c	138 A	44.6 b	36.2 c	40.4 C
L53 / COhiN	152 c	107 a-c	130 BC †	43.0 b	41.8 bc	42.4 C
L53 / F1010	163 a-c	115 ab	139 A	40.3 b	39.8 bc	40.1 C
L53 / F1028	165 ab	106 a-c	136 AB	51.6 ab	54.0 a	52.8 AB
L53 / F1029	165 ab	110 a-c	137 AB	48.5 ab	45.1 b	46.7 BC
Triton	162 a-c	117 a	140 A	51.9 ab	54.2 a	53.1 AB
ACH-R761	153 c	103 c	128 C	59.3 a	60.5 a	59.9 A
Mean	161 A	109 B	135	48.1 A	46.0 A	47.1

	Invert sugar, mg g^{-1}						Dry matter, g kg^{-1}					
L53 / CObase	2.37	a	3.90	ab	3.13	AB	234	ab	174	a-c	204	AC
L53 / F1025	0.92	b	2.61	b	1.77	D	237	ab	176	ab	206	A-C
L53 / F1026	2.23	ab	4.53	a	3.38	A	239	ab	167	a-c	203	BC
L53 / F1027	2.09	ab	2.85	b	2.47	A-D	241	ab	157	c	199	BC
L53 / COhiN	1.73	ab	3.59	ab	2.66	A-D	236	ab	159	bc	198	BC
L53 / F1010	1.81	ab	3.70	ab	2.75	A-C	248	a	172	a-c	210	AB
L53 / F1028	1.23	ab	3.88	ab	2.56	A-D	230	ab	182	a	206	A-C
L53 / F1029	1.93	ab	3.57	ab	2.75	A-C	251	a	182	a	217	A
Triton	0.94	b	3.71	ab	2.33	B-D	233	ab	164	bc	208	AB
ACH-R761	1.30	ab	2.61	b	1.96	CD	223	b	183	a	194	C
Mean	1.66	A	3.50	B	2.58		237	A	172	B	204	

†Differences among hybrids within a year followed by the same lowercase letter are not significant based upon $LSD_{0.05}$; differences among main effects followed by the same uppercase letter are not significant (P = 0.05).

nators. The amino-nitrogen concentration of the hybrid with the high amino-nitrogen pollinator, L53 cms / F1029, was 1.5 times the concentration of L53 cms / F1010 and 1.8 times the concentration of the hybrid with the low amino-nitrogen pollinator, L53 cms / F1028. The 138 ppm difference in amino-nitrogen concentration between L53 cms / F1028 and L53 cms/ F1010 was not significant.

Taken as a whole, the relative sodium, potassium, or amino-nitrogen concentration of a hybrid paralleled the individual impurity component selected during the development of the corresponding pollinator. However, the differences in concentrations of the impurity components did not necessarily result in corresponding differences in loss to molasses (Table 1), a quality measurement determined solely from the concentration of the three impurity components. The LTM concentrations of the two hybrids with pollinators selected for high amino-nitrogen concentration, L53 cms / F1029 and L53 cms / COhiN, were higher than all the other testcross hybrids. However, the difference between these hybrids and hybrids with their respective unselected parental populations, F1010 and CObase, as pollinators was significant for L53 cms / F1029 only.

The average sodium concentration of roots harvested in 2014 was 2.5 times the concentration of roots harvested in 2012 (Table 1). In contrast, the potassium concentration of roots harvested in 2014 was 6% lower than roots harvested in 2012. Consequently, the average potassium:sodium ratio in 2012 was 2.8

times the average potassium:sodium ratio in 2014 (Table 2). The average potassium:sodium ratio of the hybrid with the low sodium pollinator, L53 cms / F1025, was 1.7 times that of the hybrid with the low potassium pollinator, L53 cms / F1026. The potassium:sodium ratio of L53 cms / F1025 was also greater than the ratio of hybrids with either the high or low amino-nitrogen pollinators selected from CObase, L53 cms / COhiN and L53 cms / F1027.

Differences among hybrids in sucrose concentration were relatively small and did not appear to be associated with differences among hybrids in the concentration of sodium or potassium (Table 2). The sucrose concentration of the hybrid with F1027 as the pollinator was the only hybrid that had a higher sucrose concentration than its source (unselected) population. Since the impurity concentration of the pollinator had a relative small impact on both the loss to molasses (Table 1) and sucrose concentration (Table 2) of a hybrid, it follows that differences in recoverable sugar concentration (Table 2) were relatively small with no definitive association with the pollinator.

The only indication that the average root yield of a hybrid with a pollinator selected for an individual impurity component was different from the hybrid with its respective unselected parental pollinator was the 12.7 Mg ha^{-1} difference between L53 cms / F1028, a hybrid with a low amino-nitrogen pollinator, and L53 cms / F1010 (Table 2). The root yield of L53 cms / F1028 was 11.3 Mg ha^{-1} greater than the root yield of L53 cms / F1010 in 2012 and 14.3 Mg ha^{-1} greater than the yield of L53 cms / F1010 in 2014. Likewise, the hybrid with the low sodium pollinator, L53 cms / F1025, was the only hybrid with a lower average invert sugar concentration than the hybrid with the corresponding unselected population, CObase, as a pollinator. There was no apparent connection between the dry matter concentration of a hybrid and the sodium, potassium, or amino-nitrogen concentration of its pollinator.

Eight of the 21 correlation coefficients between pairs of variables were significant in 2012 and seven were significant in 2014 (Table 3). However, the correlation coefficients for only four variable-pairs were significant in both 2012 and 2014. These four included positive correlations between sodium concentration and root yield, potassium concentration and root yield, and between sucrose and dry matter concentration and a negative correlation between sodium and sucrose concentration. In 2014, the correlations (data not shown) between the potassium:sodium ratio and amino-nitrogen (-0.22; $P = 0.24$), sucrose (0.28; $P = 0.13$) and dry matter (0.24; $P = 0.21$) were not significant. In contrast, in 2012, the year with the higher average potassium:sodium ratios (Table 2), the correlation between the potassium:sodium ratio and amino-nitrogen concentration was -0.53 ($P < 0.01$), between the potassium: sodium ratio and sucrose concentration 0.47 ($P = 0.01$), and between potassium: sodium ratio and dry matter concentration 0.40 ($P = 0.03$).

Table 3. Correlation coefficients for pairs of variables involving sodium, potassium, amino-nitrogen, sucrose, dry matter, and invert sugar concentration and root yield, based upon hybrids grown at Fargo, ND in 2012 (above diagonal) and 2014 (below diagonal).

	Sodium	Potassium	Amino-nitrogen	Sucrose	Dry matter	Invert sugar	Root yield
	2012 (above diagonal)						
Sodium		0.44 **	0.41 **	**-0.53 ****	-0.53 **	-0.04	**0.54 ****
Potassium	0.30		-0.14	-0.12	-0.22	-0.24	**0.38 ***
Amino-nitrogen	-0.07	-0.40 *		-0.40 *	-0.19	0.09	0.12
Sucrose	**-0.43 ***	-0.17	0.15		**0.77 ****	0.06	-0.31
Dry matter	-0.10	0.12	-0.03	**0.37 ***		0.25	-0.31
Invert sugar	0.34 *	-0.18	-0.13	-0.25 *	0.15		0.08
Root yield	**0.44 ***	**0.40 ***	-0.16	-0.16	0.20	0.10	
	2014 (below diagonal)						

* and ** indicate a correlation coefficient differs significantly from zero at the 0.05 and 0.01 probability level, respectively. Correlation coefficients for pairs of variables highlighted in red were significant ($P < 0.05$) in both 2012 and 2014.

The average recoverable sucrose yield (root yield X recoverable sucrose concentration) of 7737 kg ha^{-1} in 2014 was 2733 kg ha^{-1} (CI_{95} = 2255 to 3211 kg ha^{-1}) greater than the average recoverable sucrose yield in 2012. Furthermore, differences between annual averages were significant for all variables except amino-nitrogen concentration (Table 1) and root yield (Table 2). However, even with the large annual differences in productivity and some of the variables, none of the hybrid-by-year interactions for the variables in Tables 1 and 2 were significant (P=0.05). For each variable, Spearman's rank correlation provided an indicator of the extent the ranking of the lines in 2012 corresponded to the rankings in 2014 (Table 4).

Table 4. Spearman's rank correlations comparing year-to-year consistency of rankings of hybrids (n = 10) for each variable, Fargo, ND, 2012 and 2014.

Variable	r_s	P - value
Root yield	0.71	0.03
Potassium	0.60	0.07
Sucrose	0.53	0.12
Amino-nitrogen	0.42	0.23
Invert sugar	0.42	0.23
Loss to molasses	0.38	0.28
Sodium	0.31	0.38
Recoverable sugar	0.21	0.56
Potassium:sodium ratio	0.17	0.63
Dry matter	-0.18	0.63

The correlations were significant for only two variables, potassium concentration and root yield, variables for which differences between years were small compared to some of the other traits examined. Sucrose concentration, a variable with a substantial difference between years, also had a relatively high, but not significant (P=0.12), correlation coefficient. In general, significant differences among lines within a year (Tables 1 and 2) were limited to a few extreme values with differences among most of the lines not significant. The low frequency of significant differences among lines within a year would contribute to the absence of hybrid-by-year interactions, the low Spearman's correlations between years (Table 4), and yearly differences in correlations between traits (Table 3).

DISCUSSION AND CONCLUSIONS

The relatively low sodium and potassium concentration of hybrids with low sodium (F1025) and low potassium (F1026) pollinators, respectively, indicated that pollinators with relatively low sodium or potassium concentration can substantially reduce the sodium or potassium concentration of a hybrid. It has been recognized for some time that sodium and potassium concentrations can be substantially shifted with only a few selection cycles (Powers et al., 1963; Coe, 1987; Smith and Martin, 1989; Campbell and Fugate, 2012). Dudley and Powers (1960) reported that low sodium concentration was dominant at two contrasting fertility levels, whereas, low potassium was dominant on fertilized plots and heterosis for low potassium concentration was observed on non-fertilized plots. All three impurity components, sodium, potassium, and amino-nitrogen, decreased in European commercial varieties over the 33 years examined by Hoffman et al. (2011); however, the most notable change was a 30 to 50% reduction in potassium concentration. Smith and Martin (1989) reported a higher heritability for potassium (0.66) than for sodium (0.23), suggesting that selecting for potassium may be more efficacious than selecting for sodium concentration.

The negative correlation between sodium and sucrose concentration and the positive relationship between sodium concentration and root yield and between sucrose and dry matter concentration observed in both 2012 and 2014 are consistent with the findings of others (Wood et al., 1958; Powers et al., 1959; Campbell and Kern, 1983; Campbell and Fugate, 2015). Carter (1986) observed that an increase in the sodium concentration, or a decrease in the potassium:sodium ratio, decreased dry matter concentration and reduced sucrose concentration. Tsialtas and Maslaris (2009) concluded that cultivars that limit potassium uptake while favoring sodium absorption had lower sucrose concentrations due to the dilution of sucrose caused by a decrease in dry matter concentration. The correlation between the ability of a cultivar to limit sodium in the root and amino-nitrogen concentration was positive. In nutrient solution studies with varying ratios of potassium to sodium, increased potassium favored storage root growth and sucrose accumulation (Lindhauer et al., 1990). The relatively large environmental impact on sodium concentration, relative to potassium concentration, has been observed in other trials involving some of the pollinators in this report. Over an eight-year period, the average sodium concentration for the year with the highest sodium concentration was 3.9 times the average sodium concentration in the year with the lowest sodium concentration. In contrast, there was only a 1.4 fold increase between the corresponding average potassium concentrations (Campbell and Fugate, 2012).

Differences between amino-nitrogen concentrations of lines selected for high and low amino-nitrogen concentration from a common parental population has demonstrated genetic variability for amino-nitrogen concentration. However, the increase in amino-nitrogen concentration resulting from selection for increased amino-nitrogen was often greater than the reduction observed when selection was for reduced amino-nitrogen (Ryser and Theurer, 1971; Smith and Martin, 1989; Campbell and Fugate, 2013; 2015). Following a similar pattern, roots of hybrids with pollinators selected for high amino-nitrogen concentration had higher amino-nitrogen concentrations than hybrids with pollinators selected for low amino-nitrogen concentration and hybrids with their respective unselected parental populations as pollinators. However, the difference between the reduced amino-nitrogen concentration observed for hybrids with pollinators selected for low amino-nitrogen concentration and the amino-nitrogen concentration of hybrids with the corresponding unselected parental pollinators (F1010 or CObase) was not significant. The greater selection response for increased amino-nitrogen concentration, compared to the response for reduced amino-nitrogen concentration, may be due to less genetic variance for reduced levels of amino-nitrogen as a result of past selection for increased sucrose concentration and improved processing quality in sugarbeet breeding populations (Smith and Martin 1989).

The reduction in sodium, potassium, and amino-nitrogen concentration in hybrids with pollinators selected for low concentrations of these impurities did not result in a sizeable reduction in the loss to molasses or alter the sucrose or dry matter concentration (Table 2). Therefore, differences in recoverable sugar concentrations between the hybrids with the selected pollinators and hybrids with their unselected parental populations were small and not significant. In 2012, both the average sucrose and dry matter concentration were approximately 1.4 times the average sucrose and dry matter concentration in 2014. Hence, sucrose as a percent of dry matter was similar in both years; 76.7% in 2012 and 77.3% in 2014.

The 12.8 Mg ha^{-1} difference between the average root yield of L53cms / F1028 and L53cms / F1010 was the only indication that altering an impurity component of a hybrid impacted the root yield. Additional comparisons are needed to determine if the difference between these hybrids is related to their pollinators or is a chance occurrence. In another trial, the 5-year average yield of F1028 was 3 Mg ha^{-1} greater ($P = 0.05$) than the yield of F1010 (Campbell and Fugate, 2013). The 2-year average root yield of the eight testcross hybrids was 80% of the average root yield of the two adapted hybrids. The adapted hybrids were bred for both root yield and sucrose concentration and previously met the requirements for inclusion on the list of approved varieties for commercial production in the Red River Valley of North Dakota and Minnesota.

The relatively low invert sugar concentration of L53cms / F1025 (Table 2), compared to L53cms / CObase, was not observed in previous comparisons between F1025 and CObase (Campbell and Fugate, 2012). However, the difference between the invert sugar concentration of hybrids with F1025 and F1026 as pollinators was consistent with earlier comparisons between F1025 and F1026 (Campbell and Fugate, 2012; 2015).

It appears that, when used as pollinators, lines selected for concentration of a single impurity component (sodium, potassium, or amino-nitrogen) would substantially alter the level of the corresponding impurity component of a hybrid. However, in most cases, altering only one of the impurity components resulted in only small changes in the traits normally associated with the economic value of the crop, i.e., root yield, sucrose concentration, loss-to-molasses, and recoverable sucrose per ton. Environment (years in this study) also can have a large impact on the concentration of some variables and change relationships among the components, as was observed with the potassium:sodium ratio and its relationship with sucrose, amino-nitrogen, and dry matter concentration (Tsialtas and Maslaris, 2009). A four-year trial with the pollinator lines used in this study provides further evidence that environment influences associations among impurity components and their relationships to processing quality. Lines selected for high amino-nitrogen (F1029 and COhiN) had a greater and more consistent impact on loss to molasses and recoverable sucrose concentration than any of the lines selected for a single low impurity concentration (Campbell and Fugate, 2015). Selection for an unidentified combination of impurity components, sucrose concentration, and root yield traits will be required to improve the value and productivity of the current crop. At the same time, breeders must continue to incorporate resistance to prevalent pests which vary from region to region and other agronomic traits.

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