Relative Performance of Resistant and Susceptible Sugabeet Hybrids in Environments with and without Sugarbeet Root Maggot

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ABSTRACT

Sugarbeet root maggot is a major insect pest of sugarbeet in many North American production areas. Chemical insecticides are the primary control. Host-plant resistance that ensured consistent control would provide an economically and environmentally favorable alternative to complete dependence on insecticides. A sugarbeet root maggot resistant line, F1024, selected from cultivated sugarbeet germplasm, was used to pollinate a susceptible cms line. The resulting hybrid was compared to a susceptible adapted hybrid in the presence and absence of root maggot. In a 3-year trial, there was a 1.5 Mg ha^{-1} difference in root yield between the adapted hybrid and the hybrid with the F1024 pollinator, in the absence of root maggot. In contrast, the average root yield of the susceptible adapted hybrid was 17.5 Mg ha^{-1} less than the root yield of the hybrid with the F1024 pollinator at a site with root maggot present. The reduction in damage utilizing host-plant resistance appears to be similar to the sugarbeet root maggot control obtained with insecticides.

Additional Key Words: *Beta vulgaris*, host-plant resistance, insect resistance, *Tetanops myopaeformis.*

Sugarbeet root maggot (*Tetanops myopaeformis* von Röder) (SBRM) is a major insect pest of sugarbeet (*Beta vulgaris* L.) in the central and intermountain regions of the USA and in Alberta, Canada. The larvae overwinter in the soil, migrate to near the surface in late spring, and form pupae for a short time before emerging as adult flies in the late spring. The adults migrate to recently established sugarbeet fields and deposit eggs at the base of newly emerged seedlings. The resulting larvae feed on the root surface until late July or early August (Hein et al., 2009). Reductions in yield may be the result of stand loss early in the season, but damage occurs primarily from larvae feeding throughout the growing season (Campbell et al., 1998). The primary management is chemical insecticides that reduce larval populations in sugarbeet fields (Campbell et al., 1998; Boetel et al., 2010). Root maggot resistant hybrids would provide both an economically and environmentally favorable alternative to complete dependence upon chemical insecticides (Campbell, 2005).

The first of four publically available sugarbeet germplasm lines with sugarbeet root maggot resistance, F1015, was released in 1996; followed by the release of F1016 in 1998 (Campbell et al., 2000). F1016 usually has lower root maggot damage ratings than F1015 in direct comparisons. F1015 frequently produces vigorous plants with large roots that appear to tolerate moderate feeding levels. Plants of F1016 are less vigorous, indicative of inbreeding, and produce smaller roots than those of F1015 regardless of the presence or absence of root maggot. F1024 was selected from a population formed by crossing F1016 and a Cercospora leaf spot (caused by *Cercospora beticola* Sacc.) resistant breeding line from the USDA-ARS breeding program at Ft. Collins, CO (Campbell et al., 2011). The root maggot resistance of F1024 is equal to that of F1016, but F1024 has increased resistance to leaf spot. Based upon their origins, F1015, F1016, and F1024 may have some or many of the same genes conditioning root maggot resistance. An accession with red globe-shaped roots, PI 179180, with no relation to F1015, F1016, or F1024 was the source of the root maggot resistance in a sugarbeet germplasm line released in 2016, F1043 (Campbell, 2017). Damage ratings of F1043 are similar to those observed for F1016 or F1024.

In trials encompassing six environments, four sugarbeet root maggot resistant pollinators, and five elite susceptible female (cms) lines, the yield loss attributed to root maggot feeding in hybrids with a root maggot resistant pollen parent was substantially less than the corresponding yield loss in adapted susceptible hybrids (Campbell and Niehaus, 2008; Campbell et al., 2008). Yield differences between testcross hybrids formed by crossing the eight component lines (half-sib families) of F1024 with a common susceptible cms line and adapted susceptible hybrids were small in trials at a site without root maggots, compared to the advantage of hybrids with maggot resistant pollinators at a site with heavy maggot pressure (Campbell et al., 2011).

This study compares the relative performance of a susceptible adapted hybrid with a hybrid with a maggot resistant pollinator and a susceptible female, cms parental line, in environments with and without sugarbeet root maggot. As such, it provides additional information on the effectiveness of host-plant resistance as an alternative control measure, either alone or as a part of an integrated pest management system, for sugarbeet root maggot.

METHODS AND MATERIALS

The performance of two hybrid cultivars, one a sugarbeet root maggot susceptible commercial hybrid and the other a hybrid formed by pollinating a propriety female line (Betaseed, Shakopee, MN) with sugarbeet root maggot resistant breeding lines, were compared at two locations in 2015, 2016, and 2017. Severe sugarbeet root maggot infestations are an annual occurrence at one of the locations, St. Thomas, ND, and root maggots have never caused measurable damage at the other site, Fargo, ND. The root-maggot susceptible commercial hybrid was ACH-817 (Crystal Beet Seed, Moorhead, MN). Equal seed weight of each of the eight testcross hybrids formed to evaluate the half-sib families comprising F1024 (Campbell et al., 2011) was combined and evaluated as a single root maggot resistant hybrid, designated H-1024, in the field trials.

Experimental units were either two or four 10-meter rows with 56 cm between rows. Sugarbeet root maggot damage ratings at St. Thomas were the average of a 10-root sample obtained from the first and fourth rows of each 4-row plot in late July or early August. Five consecutive roots form the center of each of the two rows were hand-dug, washed, and rated on a 0 (no damage) to 9 (more than 75% of the root surface blackened by feeding scars) scale for root maggot damage (Campbell, 2005). Stand loss, root yield, and quality estimates were obtained from the center two rows of each 4-row plot. Stand loss was the number of seedlings prior to larval feeding minus the number of roots at harvest divided by the number of seedlings, expressed as a percent. The data from Fargo were based upon measurements from 2-row plots.

The trials were planted the first two weeks of May, managed for optimum sugarbeet yield and quality throughout the growing season, and harvested in late September. Sugarbeet root maggot damage was the result of natural infestations and no attempts were made to impact the level of damage; no planting-time or postemergence insecticides were applied. Root yield was the weight of all roots from a single plot at harvest expressed as Mg ha^{-1}. Sucrose concentration, and the sodium, potassium, and amino-nitrogen concentrations that were used to calculate recoverable sugar per ton (Dutton and Huijbregts, 2006) were based upon a composite random sample of 10 – 12 roots from each plot. All yield and quality measurements are expressed on a fresh weight basis.

The experimental design was a randomized complete block with eight replicates in each of six environments, year-location combinations, and two hybrids. Fisher's Protected LSD was used to determine when differences among means were significant ($\alpha = 0.05$). The SAS GLM procedure (ver. 9.4, SAS Institute, Inc., Cary, NC) was used for the data analysis.

RESULTS

Differences among environments were significant ($P \leq 0.05$) for all variables reported in Table 1. The difference between ACH-817 and H-1024 was significant for all variables except recoverable sucrose yield. The 6-enviorment recoverable sucrose yield mean for H-1024 was 6473 kg ha^{-1}, compared to 6150 kg ha^{-1} for ACH-817. The Hybrid X Environment interaction was significant for all variables. Stand loss was the only variable for which the three Fargo environments were different (lower) than the three St. Thomas environments (Table 1). Relatively high average root yields were recorded for St. Thomas in 2015 and 2017 and Fargo 2015 with the lowest root yield observed at Fargo in 2017. Both the highest and lowest sucrose concentration and recoverable sucrose concentration occurred at Fargo, in 2017 and 2015, respectively. The highest and lowest recoverable sucrose yields, the product of recoverable sucrose concentration and root yield, were obtained at St. Thomas in 2017 and 2016 respectively.

SBRM damage ratings at St. Thomas (0 = no feeding scars to 9 = more than 75%, of the root covered with feeding scars) ranged from 2.0 for H-1024 in 2017 to 7.6 for ACH-817 in 2015 (Table 2). In all years, the damage rating for H-1024 was lower than the damage rating for ACH-817 ($P \leq 0.05$). Differences in damage ratings between ACH-817 and H-1024 ranged from 1.8 in 2017 to 3.5 in 2015 (Table 3), resulting in a significant Hybrid X Year interaction. Three-year average damage ratings for ACH-817 were 6.2, compared to 3.3 for H-1024 (Figure 1).

Along with the differences in root maggot damage ratings, difference between the stand loss of ACH-817 and H-1024 provide further evidence of the role of root maggot resistance in the relative performance of these two hybrids. Stand losses between seedling establishment and harvest of H-1024 at St. Thomas averaged 20%, ranging from 14 to 25% (Table 2). In contrast, stand losses for ACH-817 at St. Thomas averaged 40%, ranging from 36% in 2017 to 50% in 2016. The difference between ACH-817 and H-1024 was significant all three years and when averaged over all three years at St. Thomas. However, the difference in stand loss between ACH-817 and H-1024 at Fargo was not significant in any of the three years or when averaged over all three years. Stand losses at Fargo were between 7% for H-1024 in 2017 and 17% for ACH-817 in 2016 and the 4% stand loss difference between ACH-817 and H-1024 at Fargo in 2016 (Table 3) was the largest observed difference in the absence of root maggot.

The 1.5 Mg ha^{-1} 3-year average root yield difference between ACH-817 and H-1024 (Tables 2 and 3) at Fargo was not significant ($P \leq 0.05$) and the 4.9 Mg ha^{-1} advantage for ACH-817 in 2016 was the only year with a significance root yield difference between hybrids at Fargo. In

Table 1. Mean stand loss, root yield, sucrose concentration, recoverable sucrose concentration, and recoverable sucrose yield of ACH-817 and H-1024 at Fargo and St. Thomas, ND, 2015 – 2017.

Location	**Year**	**Stand loss**	**Root yield**	**Sucrose**	**Recoverable sucrose**	
		%	Mg ha^{-1}	g kg^{-1}	g kg^{-1}	kg ha^{-1}
St. Thomas	2015	24 b*	59.2 a	136 c	116 c	6792 b
	2016	37 a	38.0 b	129 d	113 c	4244 e
	2017	28 b	62.4 a	156 b	142 b	8834 a
Fargo	2015	15 c	60.5 a	128 d	86 d	5197 d
	2016	15 c	42.6 b	158 b	141 b	5971 c
	2017	8 d	41.3 b	182 a	166 a	6831 b
	Mean	**21**	**50.7**	**148**	**127**	**6311**

*Differences between environment means within a column followed by the same letter are not significant, based upon LSD ($P \leq 0.05$).

Table 2. Sugarbeet root maggot damage ratings, stand loss between seedling establishment and harvest, root yield, sucrose concentration, recoverable sucrose concentration, and recoverable sucrose yield of H-1024 and ACH-817 at St. Thomas and Fargo, ND, 2015-2017.

Hybrid	St. Thomas 2015	St. Thomas 2016	St. Thomas 2017	St. Thomas Mean	Fargo 2015	Fargo 2016	Fargo 2017	Fargo Mean
				Damage, 0 - 9				
H-1024	4.1 b*	3.9 b	2.0 b	**3.3 B**	- - -	- - -	- - -	- - -
ACH-817	7.6 a	7.0 a	3.9 a	**6.2 A**	- - -	- - -	- - -	- - -
				Stand loss, %				
H-1024	14 b	25 b	20 b	**20 B**	16 a	13 a	7 a	**12 A**
ACH-817	34 a	50 a	36 a	**40 A**	14 a	17 a	8 a	**13 A**
				Root yield, Mg ha^{-1}				
H-1024	66.8 a	51.0 a	68.1 a	**62.0 A**	58.4 a	45.1 a	43.2 a	**48.9 A**
ACH-817	51.7 b	25.0 b	56.7 b	**44.5 B**	62.6 a	40.2 b	39.4 a	**47.4 A**
				Sucrose, g kg^{-1}				
H-1024	128 b	126 b	147 b	**133 B**	116 b	147 b	170 b	**145 B**
ACH-817	144 a	133 a	165 a	**147 A**	139 a	170 a	194 a	**168 A**
				Recoverable sucrose, g kg^{-1}				
H-1024	108 b	110 b	133 b	**117 B**	76 b	129 b	154 b	**129 B**
ACH-817	124 a	116 a	151 a	**130 A**	95 a	152 a	178 a	**142 A**
				Recoverable sucrose, kg ha^{-1}				
H-1024	7180 a	5612 a	9070 a	**7278 A**	4515 a	5811 a	6650 a	**5659 B**
ACH-817	6404 a	2876 b	8597 a	**5960 B**	5878 a	6130 a	7011 a	**6340 A**

*Within a location and year, differences between hybrid means followed by the same lower case letter are not significant. Differences between 3-year means within a location followed by the same upper case letter are not significant ($P \leq 0.05$).

Table 3. Differences between the sugarbeet root maggot damage ratings, stand loss, root yield, sucrose concentration, recoverable sucrose concentration, and recoverable sucrose yield of ACH-817 and H-1024 at St. Thomas and Fargo ND, 2015 – 2017 and averaged over three years at each location and corresponding confidence intervals ($CI_{0.90}$).

	St. Thomas			Fargo		
		$CI_{0.90}$			$CI_{0.90}$	
Year	**Difference†**	**Lower**	**Upper**	**Difference**	**Lower**	**Upper**
	damage rating, 0 - 9					
2015	3.5	2.6	4.3	- - -	- - -	- - -
2016	3.2	2.6	3.7	- - -	- - -	- - -
2017	1.8	1.0	2.7	- - -	- - -	- - -
Mean	**2.8**	**2.5**	**3.2**	- - -	- - -	- - -
	Stand loss, %					
2015	19	15	23	-2	-9	4
2016	25	18	32	4	-2	10
2017	16	12	21	< 1	-10	10
Mean	**20**	**17**	**23**	**< 1**	**-3**	**4**
	Root yield, Mg ha^{-1}					
2015	-15.2	-23.7	-6.7	4.1	-9.1	17.3
2016	-26.0	-28.4	-23.7	-4.9	-7.7	-2.0
2017	-11.4	-15.0	-7.9	-3.8	-7.4	-0.2
Mean	**-17.5**	**-20.0**	**-15.1**	**-1.5**	**-5.0**	**2.0**
	Sucrose, g kg^{-1}					
2015	16.5	9.0	24.0	22.9	14.4	31.4
2016	7.0	3.8	10.1	22.3	16.0	28.6
2017	18.2	13.4	23.0	23.8	19.1	28.4
Mean	**13.9**	**11.4**	**16.4**	**23.0**	**19.9**	**26.1**
	Recoverable sucrose, g kg^{-1}					
2015	16.3	8.2	24.4	18.5	7.7	29.4
2016	5.3	1.9	8.8	22.8	15.7	30
2017	18.6	13.5	23.6	23.8	18.2	29.5
Mean	**13.4**	**10.7**	**16.1**	**21.8**	**18.0**	**25.6**
	Recoverable sucrose, kg ha^{-1}					
2015	-775	-1999	448	1363	-216	2942
2016	-2735	-3061	-2401	318	-125	762
2017	-472	-1079	134	361	-357	1079
Mean	**-1327**	**-1691**	**-965**	**680**	**220**	**1141**

†Values presented = ACH-817 average minus H-1024 average; Negative values indicate a higher value for H-1024 than for ACH-817 in that environment. Confidence intervals include 0 when the difference between ACH-817 and H-1024 is not significant (P = 0.90).

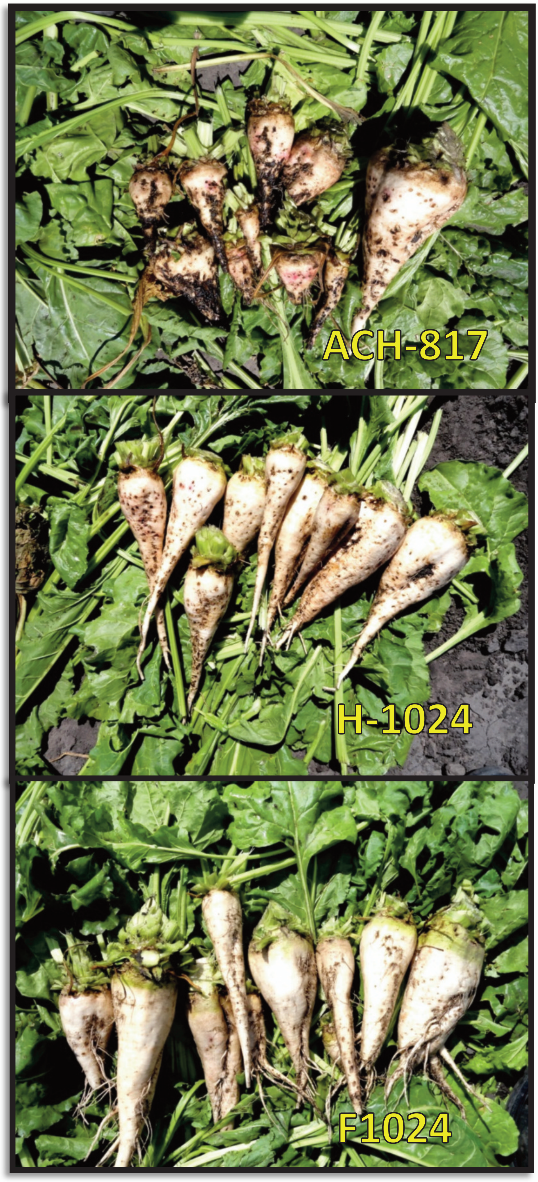
contrast, the differences between the root yields of ACH-817 and H-1024 were significant in all three years and when averaged over all three years at St. Thomas (Table 2); H-1024 had a 17.5 Mg ha^{-1} greater 3-year average root yield than ACH-817 (Table 3). In 2016, the root yield of ACH-817 was 49% of the root yield of H-1024 at St. Thomas. The largest stand loss, 50% (Table2), and stand loss compared to H-1024, 25% (Table 3), also occurred in ACH-817 at St. Thomas in 2016 (Tables 2 and 3).

Difference between the sucrose concentration of ACH-817 and H-1024 were significant in all six environments and when averaged over the six environments. The 6-environment average of ACH-817 was 158 g kg^{-1}; H-1024 had an average sucrose concentration of 139 g kg^{-1} ($LSD_{0.05} = 2$ g kg^{-1}). The sucrose concentration of ACH-817 was higher than the sucrose concentration of H-1024 in all environments. The significant Hybrid X Environment interaction for sucrose concentration was due to variation in the magnitude of the differences between the hybrids and not due to changes in rank (Table 2). The sucrose concentration of ACH-817 was 23.8 g kg^{-1} higher than the sucrose concentration of H-1024 at Fargo in 2017, compared to a 7.0 g kg^{-1} advantage at St. Thomas in 2016 (Table 3).

Recoverable sucrose concentration, an estimate of the sucrose that will be recovered in normal factory operations, is obtained by subtracting the 'loss-to-molasses' from the sucrose concentration. Loss-to-molasses is calculated based upon the concentration of sodium, potassium, and amino-nitrogen in the root. The six-environment average loss-to-molasses difference between ACH-817 and H-1024 ($P = 0.09$) and the Hybrid X Environment interaction ($P = 0.06$) were not significant (data not shown). Consequently, differences in recoverable sucrose concentration follow a pattern similar to that observed for sucrose concentration (Table 2). The recoverable sucrose concentration of ACH-817 was 23.8 g kg^{-1} higher than the sucrose concentration of H-1024 at Fargo in 2017, compared to a 5.3 g kg^{-1} advantage at St. Thomas in 2016 (Table 3).

The similar ($P = 0.06$) 6-environment average sucrose yields of ACH-817 (6150 kg ha^{-1}) and H-1024 (6473 kg ha^{-1}) masked the dependence of the relative sucrose yield of the two hybrids on the presence (St. Thomas) or absence of root maggots (Fargo). As a result of consistently higher but not significantly different sucrose yields in all three years (Table 2), the 3-year average sucrose yield of ACH-817 was 680 kg ha^{-1} ($P \leq 0.05$) greater than that of H-1024 at Fargo (Table 3). In contrast, the 3-year average sucrose yield of 5960 kg ha^{-1} at St, Thomas for ACH-817 was 1327 kg ha^{-1} less than the corresponding average of 7278 kg ha^{-1} for H-1024. The 3-year average sucrose yield of ACH-817 was 81% of the average sucrose yield of H-1024 at St. Thomas. In 2016 the sucrose yield of ACH-817 was 51% of the sucrose yield of H-1024 at St. Thomas.

Figure 1. Roots of a sugarbeet root maggot susceptible commercial hybrid, ACH-817; a hybrid, H-1024, formed by pollinating a susceptible cms line with the root maggot resistant half-sib families comprising F1024; and F1024, a root maggot resistant germplasm line. St. Thomas, ND, 2015.



DISCUSSION

Hybrid X Environment interactions occur when variability among environments elicits unique responses from different hybrids. The hybrids in this study were not related and variation among environmental factors impacting the hybrids probably was not limited to the presence or absence of sugarbeet root maggot. However, the root maggot damage ratings at St. Thomas and the differences between ACH-817 and H-1024 in relative stand losses between St. Thomas and Fargo along with the documented maggot resistance of the pollinator of H-1024 (Campbell et al., 2011) are evidence that the differences between the yields of the two hybrids was influenced substantially by the presence or absence of root maggot. Diseases that could have caused a differential response in the hybrids were not observed in any of the six environments. The environmental variation observed in these trials is not atypical of that characteristic of the region (Campbell, 1995).

The differences in the relative root and sucrose yields of the two hybrids examined in this study at St. Thomas and Fargo implies that host-plant-resistance has the potential to provide substantial protection against losses caused by sugarbeet root maggot. The 17% lower root yield of ACH-817, compared to H-1024 at St. Thomas in 2017, proceeded by a 51% lower root yield for ACH-817 in 2016, is evidence the benefits of resistance are manifest over a wide range of root maggot pressure. The sucrose concentration of ACH-817 was between 22.3 and 23.8 g kg^{-1} greater than the sucrose concentration of H-1024 at Fargo (Table 3). The smaller difference between the two cultivars at St. Thomas may be due to differential stress levels caused by root maggot feeding that prevented ACH-817 from achieving its inherent competitive sucrose concentration advantage over H-1024. The year with the largest root yield difference (26.0 Mg ha^{-1}) between the two hybrids at St. Thomas, 2016, was also the year with the smallest difference (7.0 g kg^{-1}) in sucrose concentration at St. Thomas.

The initial goal of the USDA-ARS root maggot resistance breeding effort was to determine if the available genetic variation was sufficient to allow for the selection of useful levels of resistance. Once resistance germplasm lines were available (Campbell et al., 2000; Campbell et al., 2011; Campbell 2017), there was a need to demonstrate the utility of the resistance in hybrids with root maggot resistant pollinators and susceptible elite cms lines. This report, along with others (Campbell and Niehaus, 2008; Campbell et al., 2008; Campbell et al., 2011), has confirmed that hybrids with a maggot resistant pollinator provide reliable resistance, similar to that obtained with some registered insecticides (Boetel et al., 2016; 2017). The initial phase of the breeding program focused on the development of sugarbeet root maggot resistant germplasm, as a result sucrose concentration and resistance to prevalent diseases were not emphasized. Root maggot resistance could be incorporated into elite breeding populations with commercially acceptable sucrose concentration and other desired traits by applying established breeding techniques (Campbell, 2005). A major difficulty is that selecting and evaluating germplasm for root maggot resistance requires locating nurseries and test sites in an area with a reliable infestation. Mass rearing techniques for the root maggot or artificial infestation procedures are currently not available.

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