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# Fusarium Yellows Affects Postharvest Respiration Rate, Sucrose Concentration, and Invert Sugar in Sugarbeet

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**ABSTRACT**

**Many sugarbeet (*Beta vulgaris*) processors experience increased sucrose losses during postharvest storage and reduced efficiencies when processing roots from localities with a high incidence of Fusarium yellows (causal agent, *Fusarium oxysporum* f. sp. *betae*). This study examined the effects of Fusarium yellows on root storage properties. Postharvest respiration rate, extractable sucrose concentration, and invert sugar concentration were measured on infected roots from a field with severe Fusarium yellows, a strip trial with commercial hybrids, and four trials established to assess Fusarium yellows resistance of hybrids. Postharvest respiration rates of hybrids with high disease ratings ranged from 0.85 to 2.28 mg $CO_2$ $kg^{-1}$ $h^{-1}$ higher than hybrids with low ratings, 30 days after harvest. Comparable differences in $CO_2$ production 90 days after harvest ranged from 1.36 to 3.35 mg $CO_2$ $kg^{-1}$ $h^{-1}$. A 10 kg $Mg^{-1}$ decrease in extractable sucrose accompanied each increase of 2.6 units (0 = no Fusarium yellows to 9 = severe) in the disease severity rating, 90 days after harvest. An increase in invert sugar associated with an increase in disease rating will slow processing and increase sucrose losses during processing. Since losses associated with Fusarium yellows accelerate over time, diseased roots should be processed soon after harvest.**

**Additional key words:** *Beta vulgaris*, host plant resistance.

After harvest, most of the North American sugarbeet crop (*Beta vulgaris* L.) is stored in large piles for up to 120 days prior to processing or freezing. During storage, the amount of sucrose that can be extracted is reduced by respiration, rot, conversion of sucrose to invert sugar, and physical deterioration (Campbell and Klotz, 2006a). Small reductions in the rate of storage losses can have substantial economic impact due to the large volume of roots processed and the time in storage. While it is well known that diseases that occur during the growing season affect the productivity of the crop, they also influence subsequent losses during storage (Campbell and Klotz, 2006a). Studies on the effects of Aphanomyces root rot (casual agent, *Aphanomyces cochliodes* Drechsl.) and rhizomania (caused by *Beet necrotic yellow vein virus*) on root storage properties, for example, have demonstrated that these diseases can significantly increase storage respiration rate, sucrose loss during storage, and accumulation of invert sugars which reduce processing efficiency (Campbell and Klotz, 2006b; Campbell et al., 2008; Hein et al., 2004; Klotz and Campbell 2009).

Fusarium yellows (caused by *Fusarium oxysporum* Schlect. f. sp *betae* Snyd. & Hans.), long recognized as a serious disease in the western U.S. (Hanson 2006b; Windels et al., 2005), was observed on sugarbeet in the Red River Valley of Minnesota and North Dakota in 2002 (Windels et al., 2005) and has since been reported in Michigan (Hanson, 2006b). Disease symptoms include wilting, interveinal yellowing of the leaves, and vascular necrosis (Hanson and Jacobsen, 2009). The disease is capable of causing substantial reductions in root yield, sucrose concentration, and sucrose extractability (Hanson and Jacobsen, 2009). *Fusarium* species can also cause root rot (Halverson, 2009), stalk blight in seed production fields (Hanson, 2007), seedling wilt (Hanson, 2009), and postharvest storage rot (Dunning and Byford, 1982). Some crop management options may reduce the incidence or severity of Fusarium yellows, but the most reliable control is achieved with host-plant resistance.

Development of parental lines with partial resistance to Fusarium yellows and the evaluation of hybrids are complicated by variation in disease symptoms (Martyn et al., 1989) and aggressiveness of *F. oxysporum* isolates, the presence of other *Fusarium* species, and differences in susceptibility of hybrids to different species and strains of *Fusarium* (Hanson 2007; Hanson 2009; Rivera et al., 2008; Ruppel, 1991). Patterns of variation among sugarbeet isolates of *F. oxysporum* from the U.S. indicated that *F. oxysporum* populations were distinct and endemic to their respective areas (Harveson and Rush, 1997). Differential temperature effects on colony growth and virulence provided further evidence of variation among *F. oxysporum* populations (Harveson and Rush, 1998). A unique genetic factor that causes a root tip rot in addition to the typical Fusarium yellows symptoms is present in some, but not all, *F. oxysporum* isolates (Han-

son and Jacobsen, 2006; Harveson and Rush, 1997).

Fusarium yellows-like symptoms, including vascular discoloration, similar to those resulting from inoculation with a moderately virulent *F. oxysporum* sp. *betae* isolate were observed in plants inoculated with *F. acuminatum* Ell. & Ev. Sensu Gordan, *F. avenaceum* (Fr.) Sacc., *F. moniliforme* Sheldon, and *F. solani* (Mart.) Appel & Wollenw. emend Snyd. and Han. (Hanson and Hill, 2004). Some *F. graminearum* isolates from sugarbeet with Fusarium yellows also produced foliar symptoms similar to those caused by *F. oxysporum* but with less vascular discoloration (Hanson, 2006a). An increase in Fusarium yellows severity in some *F. oxysporum* isolates and a decrease in severity by others in the presence of sugarbeet cyst nematode (*Heterodera schachtii* Schmidt) has been offered as an explanation for unexpected losses due to Fusarium yellows that have been reported by some growers planting hybrids characterized as resistant (Hanson et al., 2009).

As disease caused by *F. oxysporum*, or other *Fusarium* sp., has become more pervasive and the ability to select resistant hybrids is complicated by the multiple pathogen strains and species, concerns regarding the postharvest storage of *Fusarium*-infected roots has increased, particularly in areas were roots are stored for an extended time. Research was conducted to quantify the effect of Fusarium yellows on root storage properties. The results will assist the sugarbeet industry in determining when fields should be abandoned or processed without storage and in managing storage of diseased roots.

## MATERIALS AND METHODS

**Strip trial.** In 2004, a differential response to Fusarium yellows was observed in a non-replicated strip trial near Moorhead, MN. Symptoms included the characteristic leaf yellowing, frequently with only one side of the leaf affected, and discoloration of the vascular elements associated with Fusarium yellows (Hanson and Jacobsen, 2009). At harvest, no external rot was observed on the surfaces of the roots sampled. From this trial, seven commercial hybrids developed by four seed companies, sown in 6-row strips across the length of the field, were selected. Five 24-root samples consisting of twelve consecutive roots from each of the two center rows of each strip were hand harvested at approximately 15-m intervals on 29 Sept. 2004. Respiration rate was measured on half of the roots in each sample 30 days after harvest (DAH) and on the remaining roots 60 and 120 DAH. Sucrose and extractable sucrose concentration of each sample were determined 30 and 120 DAH. One hundred-twenty days after harvest, the 12 roots in each sample were cut longitudinally and the proportion of rotted tissue visually rated on a 0 (no rot) to 9 (almost all tissue rotted) scale. Individual root ratings were averaged to obtain a rot index for the sample.

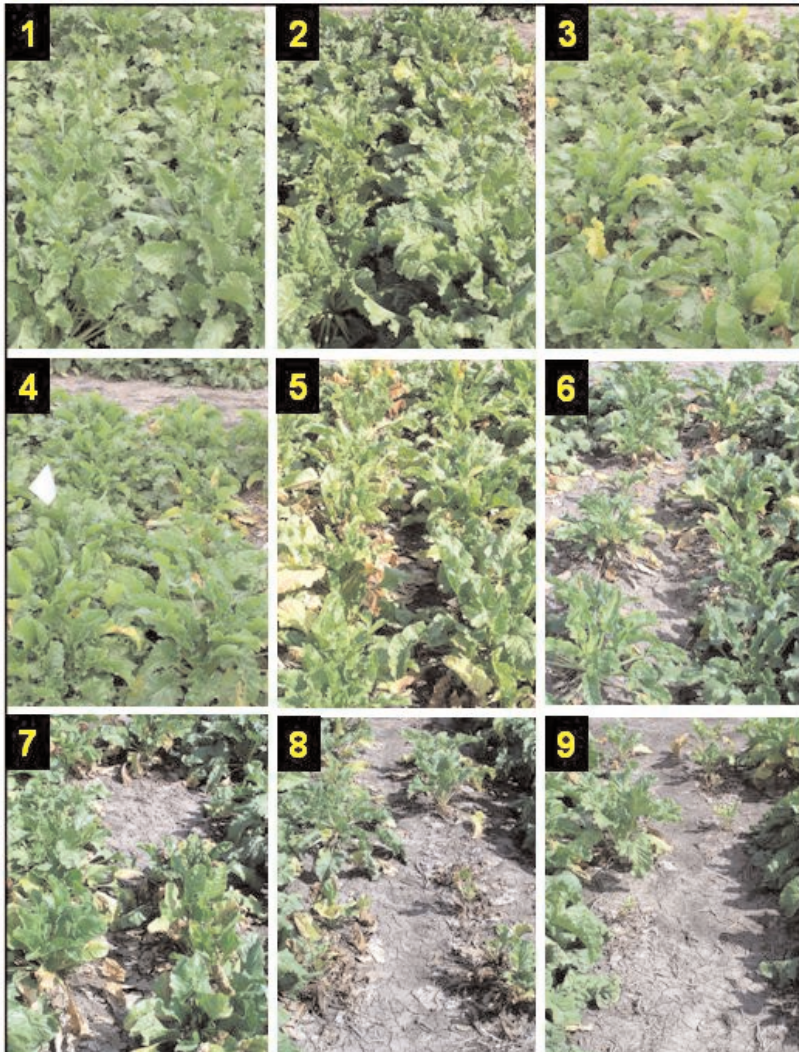
**Commercial field.** In 2006, roots from two 12-row strips left for insurance adjustors in a commercial field south of Felton, MN that had been abandoned because of severe Fusarium yellows were harvested on 15 Sept. One hundred-eight roots from a small area (< 0.10 ha) of each strip were divided into three groups of 36, with roots within a group exhibiting similar mild, intermediate, or severe Fusarium yellows foliar symptoms. Vascular elements of infected roots exhibited the discoloration associated with Fusarium yellows (Hanson and Jacobsen, 2009). No external rot was observed on the surface of the roots sampled. The three groups corresponded to ratings of 1 to 3, 4 to 6, and 7 to 8, respectively, based upon the 1 to 9 foliar disease rating scale portrayed in Fig. 1. The 36 roots within a group were randomly assigned to three 12-root samples which comprised the experimental units for subsequent observations. The two strips were treated as replicates and the groups as treatments for the analysis of variance. Respiration rate was measured on all three samples from each replicate and disease group 30 DAH and on two samples 60, 90, and 120 DAH. Sucrose and extractable sucrose were measured on one sample from each disease group and replicate 30 DAH and on two samples from each disease group and replicate 120 DAH.

**Hybrid assessment trial.** In 2006, 2007, and 2008, roots were harvested from four American Crystal Sugar Co. (Moorhead, MN) trials established to assess Fusarium yellows resistance of hybrids. The four trials had a wide range of Fusarium yellows symptoms among the hybrids and very few, or no symptoms of other diseases that might impact postharvest storage losses. Each year's trial included all the hybrids approved for commercial production in the region that year and promising experimental hybrids vying for approval. Twelve hybrids from a trial near Sabin, MN were harvested 27 Sept. 2006; 13 hybrids were harvested from trials near Sabin and Moorhead, MN on 27 and 28 Sept 2007, and 15 hybrids were harvested from a trial near Moorhead, MN on 17 Sept 2008. The hybrids were arranged in a randomized complete block design at each site. Roots were harvested from six replicates in 2006 and 2007 and four replicates in 2008. Eight to 14 roots were harvested from the center of each plot. Plots were 2 rows wide and 4 m long with 56 cm between rows. Each environment was analyzed as a separate experiment.

Natural populations of *Fusarium* spp. were the sole source of inoculum. Disease severity, based upon foliar expression, was rated on a one to nine scale in which one was a full stand of healthy plants and nine indicated all or most plants were dead (Fig. 1). Hybrids were rated on two dates by two individuals each year and the average of the four disease ratings was used in the data analysis. The first ratings were recorded in late-June to mid-July, shortly after symptoms appeared and differences among hybrids were apparent. The second ratings were recorded mid-September. The number of hybrids in the trials ranged from 25 in 2006 to 96 in 2008. Hybrids within a trial

were listed in order of their disease rating. Every other hybrid on the list was selected for storage evaluations in 2006; every fourth hybrid on the list was selected in 2007, and every sixth hybrid was selected in 2008. Selection of the hybrids for the 2007 storage evaluations was based upon the combined disease ratings for the two locations and the same hybrids were harvested at both locations.

**Fig. 1.** Foliar symptoms corresponding to Fusarium yellows disease ratings (Sabin, MN, 11 September 2006; courtesy of American Crystal Sugar Co., Moorhead, MN).



Each year the hybrids were identified by a code number, with the seed company and hybrid designation maintained as proprietary information. Therefore, it is not known which, if any, of the hybrids were evaluated in more than one year.

**Sample material and data collection.** For all trials, harvested roots were promptly transported to Fargo, ND, washed, and placed in perforated plastic produce bags. Roots were then placed on shelves in a room maintained at 4.5° C and 90-95% relative humidity. Respiration rate was determined by placing an 8 to 14-root sample in a 23-liter sealed bucket equipped with inlet and outlet tubes through which ambient air was continuously circulated at a flow rate of 475 mL $min^{-1}$. After 24 h, the $CO_2$ concentration of the air from the exit tube was determined with an infrared $CO_2$ analyzer (Licor LI-6252, Lincoln, NE). The $CO_2$ concentration of ambient air from the exit tube of an empty bucket was subtracted from this measurement and the respiration rate expressed as mg $CO_2$ produced per kg of roots per hour.

Sucrose concentration and purity were used to calculate extractable sucrose concentration (Dexter et al., 1967). Extractable sucrose is an estimate of the total sucrose in the root that can be extracted using standard sugar factory operations, expressed as kg sucrose per Mg of roots. Sucrose was determined polarimetrically (McGinnis, 1982). The purity (sucrose as a percent of dry substance) measurements needed to calculate extractable sucrose concentration were determined using the procedures described by Dexter et al. (1967). Sucrose and extractable sucrose concentrations for samples from the 2004 strip trial and the 2006 field samples 30-DAH were expressed on a fresh weight basis. Sucrose concentrations for the samples 120-DAH were adjusted to account for slight changes in dry matter concentration between sampling dates and expressed on a dry matter concentration equal to the corresponding sample 30 DAH. A portion (20 g) of each brei (fine beet particles; the product of a beet saw) sample used to measure sucrose concentration was weighed, oven dried at 80° C, and weighed again to calculate dry matter concentration.

Glucose and fructose concentrations were determined colorimetrically using end point, enzyme-coupled assays (Klotz and Martins, 2007; Spackman, 2001). Assays were conducted in 200 µL volumes using 5 µL of the extracts prepared for polarimetric sucrose determinations. Glucose, fructose, and invert sugar (glucose + fructose) concentrations are reported as grams per 100 grams of sucrose (g/100S), which was measure colorimetrically on the same sample that was used to determine glucose and fructose concentrations.

**Statistical analyses.** Hybrid means within an environment were compared using Fisher's protected least significant difference with $\alpha = 0.10$. The 10% significance was chosen over the frequently used 5% level to reduce the probability of committing a type II error. When

selecting hybrids with resistance to potential disease problems, the economic consequences of declaring two hybrids equal when, in fact, they are different (a type II error) often are greater than concluding two hybrids are different when they are actually equal (a type I error with probability equal to the significance level). Decreasing the probability of a type I error ($\alpha$) increases the probability of committing a type II error (Carmer, 1976). In addition to the analysis of variance, correlation analysis was used to determine associations between relevant variables. In addition to resistance to Fusarium yellows, inherent differences in respiration rate, sucrose concentration, resistance to other diseases that may have been present at low levels, and abiotic factors affect the traits examined. To reduce the influence of these confounding factors and quantify only the importance of Fusarium yellows resistance, the four hybrids with the lowest disease ratings were contrasted with the four hybrids with the highest disease rating. The "Estimate" function of the SAS GLM procedure (SAS 9.1 SAS Institute, Inc., Cary, NC) was used to calculate the magnitude of the difference between the resistant and the susceptible groups of hybrids.

Simple regression analysis, with Fusarium yellows severity as the independent variable and respiration rate, extractable sucrose concentration, or invert sugar concentration as dependent variables, was employed to quantify the relationship between disease severity and storage losses. The respiration rate, extractable sucrose, and invert sugar data from each environment were standardized to a common mean and variance using the PROC STANDARD procedure (SAS 9.1). The mean of the standardized data was equal to the overall mean of each trait and the variance was the mean of the variances of the four environments.

## RESULTS

**Strip trial.** Trends that seem apparent in a single strip-trial should be viewed with considerable caution. However, the relationships between disease severity and sucrose loss and respiration rate observed in the 2004 trial (Table 1) indicated that the impact of Fusarium yellows on yield and storage losses warranted further examination. Rot indices after storage for 120 days ranged from 1.2 for Hybrid A to 6.3 for Hybrid G. A few roots of Hybrid A had vascular discoloration typical of Fusarium yellows (Hanson and Jacobsen, 2009) in the center of the root but very little rotted tissue. Roots with vascular discoloration were more frequent in Hybrid B, but very little rotted tissue was observed 120 DAH. All the other hybrids had more rotted tissue than A or B, with Hybrid G having the most rot. Thirty days after harvest, the respiration rate of Hybrid G was 1.9 times the respiration rate of Hybrid A, 60 DAH the respiration rate of G was 2.4 times that of A, and by 120 DAH G had a respiration rate 3.4

**Table 1.** Respiration rate 30, 60, and 120 days after harvest (DAH), sucrose and extractable sucrose concentration, daily sucrose loss during storage, and rot rating of seven adapted commercial sugarbeet hybrids, Moorhead, MN 2004[†].

| | Respiration rate (mg $CO_2$ $kg^{-1}$ $h^{-1}$) | | | Sucrose ($kg\ Mg^{-1}$)[§] | | Extractable Sucrose ($kg\ Mg^{-1}$)[§] | | | Rot[¶] |
|---|---|---|---|---|---|---|---|---|---|
| **Hybrid** | **30 DAH[‡]** | **60 DAH** | **120 DAH** | **30 DAH** | **120 DAH** | **30 DAH** | **120 DAH** | **Loss $day^{-1}$** | **(0 - 9)** |
| A | 5.35 c | 6.32 d | 9.47 c | 148 a | 136 a | 126 a | 111 a | 0.16 d | 1.2 c |
| B | 5.53 bc | 6.62 d | 11.48 c | 133 bc | 111 bc | 110 b-d | 84 b | 0.29 cd | 1.4 c |
| C | 6.73 bc | 10.51 b | 18.94 b | 125 c | 96 c | 101 d | 67 bc | 0.38 bc | 2.8 b |
| D | 5.29 c | 6.53 d | 20.11 b | 140 ab | 119 ab | 117 ab | 74 bc | 0.48 a-c | 3.0 b |
| E | 5.38 c | 7.72 cd | 18.97 b | 131 c | 96 c | 106 cd | 61 c | 0.50 ab | 3.4 b |
| F | 7.14 b | 9.61 bc | 22.53 b | 141 ab | 97 c | 115 bc | 59 c | 0.62 a | 3.8 b |
| G | 10.06 a | 15.43 a | 31.78 a | 106 d | 54 d | 80 e | 24 d | 0.61 a | 6.3 a |
| **Mean** | **6.49** | **8.96** | **19.18** | **132** | **101** | **108** | **68** | **0.44** | **3.1** |

[†] Differences among means within a column followed by the same letter are not significant according to Fisher's protected least significant difference (P = 0.10). Values are the mean of five twelve-root samples.
[‡] DAH = days after harvest (29 September 2004).
[§] Sucrose and extractable sucrose concentrations: 30 DAH, fresh weight basis; 120 DAH, adjusted to dry matter concentration at 30 DAH.
[¶] Rot rating: roots cut longitudinally and visually rated 120 DAH; 0 = no internal rot to 9 = completely rotted.

times that of A. Similarly, the 42 kg $Mg^{-1}$ difference in sucrose concentration between Hybrids A and G 30 DAH increased to 82 kg $Mg^{-1}$ 120 DAH. During the 90 days between sampling dates, the extractable sucrose loss for Hybrid A was 12% of the 30-DAH concentration, compared to a 70% loss for Hybrid G. In general, there appeared to be a close relationship between rot severity, postharvest respiration rate, sucrose concentration, extractable sucrose concentration, and sucrose loss during storage with the negative impact of the rot increasing over time. *Fusarium oxysporum* and *F. solani* were isolated from root vascular tissue of diseased roots from the site. Other fungi found in soil from the site which also cause symptoms similar to Fusarium yellows, *F. avenaceum* or *F. acuminatum* and *Verticillium* spp., were not found in any of the roots (personal communication: A. L. Cattanach, Am. Crystal Sugar Co.; fungi identified by L.E. Hanson, USDA-ARS).

**Commercial Field.** An apparent positive relationship between Fusarium yellows severity and sucrose losses during storage observed in samples from the commercial field in 2006 (Table 2) was consistent with observations from the 2004 strip-trial (Table 1). Respiration rate increased in all groups over time; however, the increase was greatest in the severe disease group. Thirty days after harvest, the respiration rate of the severe group was 3.4 times that of the group with mild symptoms (Table 2). By 120 DAH the respiration rate of the mild group was 1.6 times its 30 DAH rate while the respiration rate of the severe group was 2.6 times its 30 DAH value. Consequently the 120 DAH respiration rate of the severe group increased to 5.4 times that of the mild group. Thirty days after harvest, the extractable sucrose concentration of the severe group was 41% of the mild group. During the 90 days between sampling, the extractable sucrose loss was 13 kg $Mg^{-1}$ for the mild group, compared to 40 kg $Mg^{-1}$ for the severe group, and 24 kg $Mg^{-1}$ for the intermediate group. Based upon the 0.31 kg $Mg^{-1}\,d^{-1}$ difference in extractable sucrose loss (Table 2), roots in the severe group would lose 10 kg more sucrose per ton (Mg) than the mild group each 32 days in storage. Eighty-three days in storage would be needed for the intermediate group to lose 10 kg $Mg^{-1}$ more sucrose than the mild group.

**Hybrid assessment trial.** In the 2006 to 2008 evaluation trials, there were significant differences among hybrids in disease severity (Table 3), based upon foliar symptoms (Fig. 1). The largest contrast among the hybrids was observed at Moorhead in 2008 where disease ratings ranged from 1.2 to 7.7. With the exception of Sabin in 2007, the disease ratings of the four hybrids with the highest ratings were significantly higher than the ratings for the four hybrids with the lowest ratings. In the 2007 Sabin trial, the disease ratings of the three hybrids with the highest disease ratings were significantly higher than the four hybrids with the lowest disease ratings. *Fusarium graminearum*, *F. sambucinum* (syn. *F. sulphureum*), *F. oxyspo-*

**Table 2.** Respiration rate 30, 60, 90, and 120 days after harvest (DAH), sucrose and extractable sucrose concentration, and daily sucrose loss during storage of sugarbeet roots with Fusarium yellows, Felton, MN 2006‡.

| Fusarium Yellows† | Respiration rate (mg $CO_2$ $kg^{-1}$ $h^{-1}$) | | | | Sucrose (kg $Mg^{-1}$)¶ | | Extractable Sucrose (kg $Mg^{-1}$)§ | | |
|---|---|---|---|---|---|---|---|---|---|
| | 30 DAH§ | 60 DAH | 90 DAH | 120 DAH | 30 DAH | 120 DAH | 30 DAH | 120 DAH | Loss $day^{-1}$ |
| Mild | 3.59 c | 4.51 c | 5.06 c | 5.92 c | 159 a | 150 a | 135 a | 122 a | 0.14 b |
| Intermediate | 5.68 b | 9.34 b | 13.32 b | 17.29 b | 126 b | 105 b | 96 b | 72 b | 0.26 b |
| Severe | 12.12 a | 19.18 a | 23.54 a | 31.69 a | 82 c | 51 c | 56 c | 16 c | 0.45 a |
| **Mean** | **7.13** | **11.01** | **13.97** | **18.3** | **122** | **102** | **96** | **70** | **0.29** |

† Disease severity classes based upon foliar Fusarium yellow symptoms; Mild = disease ratings of 1-3, Intermediate = ratings of 4-6, and Severe = ratings of 7-8 on a 1=healthy to 9=severe scale .

‡ Differences among means within a column followed by the same letter are not significant, according to Fisher's protected least significant difference (P=0.10). Values for 30 DAH respiration rates are means of six twelve-root samples; 60, 90, and 120 DAH respiration rates are means of four twelve-root samples. Sucrose and extractable sucrose values 30 DAH are the mean of two twelve- root samples; 120 DAH values are the mean of four samples.

§ DAH = days after harvest (15 September 2006).

¶ Sucrose and extractable sucrose concentrations: 30 DAH, fresh weight basis; 120 DAH, adjusted to dry matter concentration at 30 DAH.

*rum* and an unidentified novel *Fusarium* species were isolated from diseased roots from the Fusarium evaluation sites; all four species were pathogenic on sugarbeet in greenhouse trials (Burlakoti et al., 2007; Hanson, 2006a; Rivera et al., 2008).

In general, differences in respiration rate among hybrids 30 and 90 DAH increased as disease ratings increased (Table 3). The respiration rate of hybrid 603 at Sabin in 2006 was 1.6 times the respiration rate of 611 30 DAH; 90 DAH the respiration rate of 603 was 2.3 times that of 611. In 2007, 30 DAH, the respiration rate of the hybrid with the highest disease rating, 701, was 1.7 and 2.1 times that of hybrid 712 at Sabin and Moorhead, respectively. By 90 DAH the respiration rate of 701 was 2.1 times the respiration rate of 712 at Sabin and 3.7 times the respiration of 712 at Moorhead. Similarly, at Moorhead in 2008, 30 DAH the respiration rate of 802, a hybrid with a high disease rating, was 1.9 times that of 815, the hybrid with the lowest disease rating; 90 DAH the respiration rate of 802 was 2.8 times that of 815.

While extractable sucrose concentration provides an estimate of the amount of sucrose a processor can expect from a quantity of roots, the proportion of the total sucrose that can be extracted (extractable sucrose divided by sucrose) provides processors an indicator of factory efficiency. The extraction percent ranged from 84% for a hybrid with a high disease rating (601) to 86% for two hybrids (610 and 611) with low disease ratings at Sabin in 2006. In 2007, the hybrid with the highest disease rating (701) had extraction rates of 80 and 46% at Sabin and Moorhead, respectively. In contrast, a hybrid with a relatively low disease rating (713) and a hybrid with an intermediate rating (706) had extraction rates of 89% at Sabin and 82% at Moorhead. Sucrose extraction rates at Moorhead in 2008 ranged from 75% for the hybrid with the highest disease rating (801) and a hybrid with an intermediate disease rating (806) to 89% for the hybrid with the lowest disease rating (815).

Glucose, fructose and invert sugar concentrations were generally elevated in hybrids with the greatest disease symptom ratings (Table 3). Between hybrids with the highest and lowest disease ratings, glucose concentrations were elevated 3.3- and 2.8-fold at Moorhead in 2007 and 2008; fructose concentrations were elevated 2.5- and 6.5-fold at Sabin in 2007 and Moorhead in 2007. The combined concentrations of glucose and fructose, i.e., the invert sugar concentration of hybrids with the highest disease ratings was 2.1-, 4.3-, and 2.7-fold greater the invert sugar concentration of hybrids with the lowest disease ratings at Sabin in 2007, Moorhead in 2007, and Moorhead in 2008, respectively. Although sucrose contains equimolar concentrations of glucose and fructose moieties, glucose concentrations were generally greater than fructose concentrations in roots from all environments regardless of disease severity rating.

In all of the 2006 to 2008 evaluation trials, disease rating was pos-

**Table 3.** Disease rating, respiration rate 30 and 90 days after harvest (DAH), and sucrose, extractable sucrose, and invert sugar concentration (90 DAH) of adapted sugarbeet hybrids, Sabin, MN 2006 and 2007 and Moorhead, MN 2007 and 2008[‡].

| | | | Respiration rate ($mg\ CO_2\ kg^{-1}\ h^{-1}$) | | | | Invert sugars (g/100 g sucrose) | | |
|---|---|---|---|---|---|---|---|---|---|
| Location | Hybrid | Disease Rating[†] | 30 DAH[§] | 90 DAH | Sucrose[¶] | Extractable sucrose[¶] | Glucose | Fructose | Total |
| 2006 | 601 | 5.8 a | 4.83 bc | 4.75 cd | 149 d | 125 d | - - - | - - - | - - - |
| Sabin | 602 | 4.5 b | 5.10 ab | 6.21 ab | 123 e | 94 e | - - - | - - - | - - - |
| | 603 | 3.9 c | 5.09 a | 7.42 a | 131 e | 101 e | - - - | - - - | - - - |
| | 604 | 3.7 c | 5.08 ab | 5.00 bc | 126 e | 102 e | - - - | - - - | - - - |
| | 605 | 2.9 d | 3.97 c-e | 3.48 ce | 158 b-d | 135 a-d | - - - | - - - | - - - |
| | 606 | 2.8 de | 4.64 b-d | 4.28 c-e | 172 a | 147 a | - - - | - - - | - - - |
| | 607 | 2.5 de | 3.89 de | 3.68 c-e | 163 a-c | 138 a-c | - - - | - - - | - - - |
| | 608 | 2.5 de | 3.62 e | 4.32 c-e | 159 b-d | 132 b-d | - - - | - - - | - - - |
| | 609 | 2.4 d-f | 4.17 c-e | 4.20 c-e | 155 dc | 130 dc | - - - | - - - | - - - |
| | 610 | 2.3 d-f | 3.73 e | 3.65 c-e | 168 ab | 144 ab | - - - | - - - | - - - |
| | 611 | 2.2 ef | 3.28 e | 3.17 e | 163 a-c | 140 a-c | - - - | - - - | - - - |
| | 612 | 1.8 f | 3.63 e | 3.52 de | 154 dc | 132 b-d | - - - | - - - | - - - |
| **Mean** | | **3.1** | **4.32** | **4.47** | **152** | **127** | **- - -** | **- - -** | **- - -** |
| 2007 | 701 | 6.0 a | 5.81 a | 6.73 a | 113 f | 90 f | 1.84 a | 1.41 a | 3.25 a |
| Sabin | 702 | 4.4 b | 4.18 b-d | 4.20 bc | 150 e | 129 e | 1.14 a | 0.52 b-d | 1.65 c-e |
| | 703 | 4.1 b | 4.53 b | 4.47 b | 159 d | 138 d | 1.55 a | 0.85 b | 2.39 bc |
| | 704 | 3.3 c | 4.05 b-d | 3.69 c-e | 172 a-c | 150 a-c | 1.54 a | 0.66 b-d | 2.20 b-d |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 705 | 3.2 c | 4.23 b-d | 3.79 b-e | 170 bc | 149 bc | 1.34 a | 0.66 b-d | 2.00 b-e |
| | 706 | 3.0 cd | 3.94 c-e | 3.91 b-d | 175 ab | 156 ab | 1.78 a | 0.71 b-d | 2.50 ab |
| | 707 | 3.0 cd | 4.36 bc | 4.20 bc | 169 bc | 150 bc | 1.39 a | 0.72 b-d | 2.12 b-e |
| | 708 | 2.9 c-e | 3.92 c-f | 3.70 c-e | 170 bc | 150 b | 0.60 a | 0.79 bc | 1.39 e |
| | 709 | 2.9 c-e | 3.35 f | 3.26 de | 172 a-c | 152 a-c | 1.29 a | 0.40 d | 1.69 c-e |
| | 710 | 2.8 c-e | 4.13 b-d | 3.48 de | 178 a | 158 a | 1.23 a | 0.82 bc | 2.07 b-e |
| | 711 | 2.6 d-f | 3.77 d-f | 3.32 de | 172 a-c | 153 a-c | 1.22 a | 0.53 b-d | 1.75 b-e |
| | 712 | 2.4 ef | 3.39 ef | 3.14 e | 165 cd | 146 c | 0.98 a | 0.47 cd | 1.46 de |
| | 713 | 2.1 f | 3.89 c-f | 3.68 c-e | 169 bc | 150 bc | 1.03 a | 0.56 b-d | 1.58 de |
| **Mean** | | **3.3** | **4.12** | **3.97** | **164** | **144** | **1.30** | **0.70** | **2.00** |
| 2007 | 701 | 6.7 a | 9.10 a | 13.78 a | 61 e | 28 f | 4.92 a | 4.20 a | 9.12 a |
| Moorhead | 702 | 5.9 b | 6.12 b | 4.95 b-d | 116 d | 90 e | 2.04 cd | 1.34 b-e | 3.38 b-e |
| | 708 | 4.6 c | 5.13 b-d | 5.23 bc | 138 a | 113 a | 2.63 b-d | 1.70 bc | 4.33 bc |
| | 704 | 4.5 c | 5.62 bc | 4.97 b-d | 125 a-d | 96 c-e | 2.63 b-d | 1.54 b-d | 4.16 b-d |
| | 706 | 4.5 c | 4.73 c-e | 4.47 b-d | 123 cd | 101 a-e | 3.05 bc | 1.93 b | 4.98 b |
| | 703 | 4.4 c | 5.75 bc | 5.36 b | 119 cd | 94 e | 1.52 d | 0.92 d-f | 2.44 de |
| | 707 | 3.8 d | 4.93 c-e | 4.66 b-d | 122 cd | 95 de | 1.94 cd | 1.05 c-f | 2.98 c-e |
| | 710 | 3.5 de | 5.63 bc | 4.70 b-d | 136 ab | 109 ab | 2.23 b-d | 1.41 b-e | 3.64 b-e |
| | 705 | 3.4 de | 4.89 c-e | 3.70 d | 136 ab | 108 a-c | 3.49 b | 0.93 d-f | 4.43 bc |
| | 709 | 3.1 ef | 3.96 e | 3.85 cd | 124 b-d | 100 b-e | 1.64 d | 0.78 ef | 2.42 de |
| | 713 | 2.8 fg | 4.72 c-e | 3.65 d | 132 a-c | 108 a-d | 1.85 cd | 0.85 ef | 2.70 c-e |
| | 711 | 2.6 fg | 3.85 e | 4.29 b-d | 130 a-c | 103 a-e | 1.88 cd | 0.95 d-f | 2.83 c-e |
| | 712 | 2.3 g | 4.31 de | 3.75 d | 131 a-c | 107 a-d | 1.47 d | 0.65 f | 2.12 e |
| **Mean** | | **4.0** | **5.29** | **5.18** | **122** | **96** | **2.41** | **1.40** | **3.81** |

*(Table Continued on Next Page)*

**Table 3 *(Con't).*** Disease rating, respiration rate 30 and 90 days after harvest (DAH), and sucrose, extractable sucrose, and invert sugar concentration (90 DAH) of adapted sugarbeet hybrids, Sabin, MN 2006 and 2007 and Moorhead, MN 2007 and 2008[‡].

| | | | Respiration rate ($mg\ CO_2\ kg^{-1}\ h^{-1}$) | | | | Invert sugars (g/100 g sucrose) | | |
|---|---|---|---|---|---|---|---|---|---|
| Location | Hybrid | Disease Rating[†] | 30 DAH[§] | 90 DAH | Sucrose[¶] | Extractable sucrose[¶] | Glucose | Fructose | Total |
| 2008 Moorhead | 801 | 7.7 a | 7.01 cd | 6.40 b-e | 113 ef | 85 ef | 4.33 a-c | 1.57 a-d | 5.90 bc |
| | 802 | 7.4 ab | 8.90 a | 10.76 a | 107 f | 81 f | 6.44 a | 2.60 a | 9.04 a |
| | 803 | 6.9 bc | 6.91 dc | 5.60 c-f | 116 d-f | 90 c-f | 2.51 c-e | 1.30 cd | 3.82 b-d |
| | 804 | 6.5 c | 6.68 c-e | 6.29 b-e | 123 b-e | 95 b-e | 2.08 de | 1.41 b-d | 3.50 cd |
| | 805 | 5.7 d | 7.03 b-d | 7.05 bc | 121 b-e | 92 c-f | 4.76 ab | 2.00 a-c | 6.76 ab |
| | 806 | 5.6 d | 8.39 ab | 7.77 b | 117 c-f | 88 d-f | 4.26 a-d | 2.43 ab | 6.69 ab |
| | 807 | 5.4 d | 5.68 d-g | 5.23 c-f | 129 bc | 108 b | 1.88 e | 1.31 cd | 3.19 cd |
| | 808 | 5.3 d | 6.35 d-f | 5.81 b-f | 127 b-d | 102 bc | 1.64 e | 1.22 cd | 2.86 d |
| | 809 | 4.2 e | 7.86 a-c | 6.87 b-d | 130 b | 103 bc | 2.86 b-e | 1.36 cd | 4.22 b-d |
| | 810 | 3.1 f | 4.71 g | 4.66 ef | 130 b | 105 b | 1.48 e | 0.75 d | 2.28 d |
| | 811 | 2.7 jg | 5.44 e-g | 5.57 c-f | 129 bc | 101 b-d | 1.97 e | 0.85 d | 2.83 d |
| | 812 | 2.7 fg | 5.18 fg | 4.50 ef | 131 b | 106 b | 2.64 b-e | 1.33 cd | 3.96 b-d |
| | 813 | 2.2g | 6.70 c-e | 5.70 b-f | 120 b-e | 99 b-e | 1.41 e | 1.92 a-c | 3.33 cd |
| | 814 | 2.0 g | 5.94 d-g | 4.93 d-f | 129 bc | 107 b | 2.59 b-e | 2.59 b-d | 4.02 b-d |
| | 815 | 1.2 h | 4.71 g | 3.78 f | 158 a | 141 a | 1.55 e | 0.60 d | 2.15 d |
| **Mean** | | **4.6** | **6.48** | **6.06** | **125** | **100** | **2.83** | **1.47** | **4.30** |

[†] Rated on a 1 – 9 scale based upon foliar symptoms (1 = full stand of healthy plants to 9 = all or most plants dead).

[‡] Differences among means within a column and year/location followed by the same letter are not significant according to Fisher's least significant difference (P = 0.10). Values are means of six replicates in 2006 and 2007; four replicates in 2008.

[§] DAH = days after harvest (27 September 2006, 27-28 September 2007, and 17 September 2008).

[¶] Sucrose and extractable sucrose concentrations ($kg\ Mg^{-1}$).

itively correlated with respiration rate 30 and 90 DAH and negatively associated with sucrose and extractable sucrose concentration (Table 4). Sucrose and extractable sucrose concentration also were negatively correlated with respiration rate 30 and 90 DAH. Exceptions to this trend include the non-significant difference in sucrose and extractable sucrose concentrations between hybrids 601 and 612, the hybrids with the highest and lowest disease ratings, respectively, at Sabin in 2006 and hybrid 708, a hybrid with a high disease rating which also had a relative high sucrose and extractable sucrose concentration at Moorhead in 2007.

In the 2007-2008 trials, glucose and fructose concentration were positively correlated with disease rating. The only correlations that were not significant involved glucose concentration and respiration rate, sucrose concentration, extractable sucrose concentration, or fructose concentration at Sabin in 2007. This most likely was caused by the absence of significant differences among hybrids (Table 3) in glucose concentration in that environment.

Although the differences in disease ratings indicated that hybrids had differing levels of resistance to Fusarium yellows, it was not possible to place hybrids in distinct groups based upon their disease ratings (Table 3). Furthermore, environmental factors and inherent differences in traits other than Fusarium yellows resistance can impact relative respiration rates and sucrose concentration and extractability. To examine the impact of Fusarium yellows on the other traits measured and minimize the influence of factors other than Fusarium yellows severity, the average of the four hybrids with the lowest disease ratings was contrasted with the average of the four hybrids with the highest disease ratings for each trait (Table 5). In all environments, the respiration rate of the susceptible group was higher than the respiration rate of the resistant group. The magnitude of the difference ranged from 0.85 to 2.28 mg $CO_2$ kg-1 $h^{-1}$ 30 DAH and from 1.36 to 3.35 mg $CO_2$ $kg^{-1}$ $h^{-1}$ 90 DAH. The difference between respiration rates of the two groups 90 DAH was always greater than the corresponding difference 30 DAH. The average of the four hybrids comprising the resistant group had from 19 to 28 kg more sucrose and from 22 to 31 kg more extractable sucrose per ton (Mg) than the susceptible group. Furthermore, invert sugar concentration also was greater in the susceptible group than in the resistant group. The number of roots available from the 2006-2008 hybrid evaluation trials (Table 3) was insufficient for sucrose and invert sugar determinations 30 DAH. Therefore, the sucrose, extractable sucrose, and invert sugar concentrations reported include both preharvest and postharvest losses caused by Fusarium yellows.

Regression analyses provided additional verification of the detrimental effects of Fusarium yellows on sugarbeet roots during storage. The relatively small difference between the intercepts for respiration rate 30 and 90 DAH (Fig. 2A and 2B) and the average respiration

**Table 4.** Correlation coefficients for disease rating, respiration rate, sucrose, extractable sucrose, glucose, and fructose of sugarbeet hybrids, Sabin, MN 2006 and 2007 and Moorhead, MN 2007 and 2008[†].

| Year / location | | Disease rating | Respiration rate 30 DAH | Respiration rate 90 DAH | Sucrose | Extractable Sucrose | Glucose | Fructose |
|---|---|---|---|---|---|---|---|---|
| 2006 Sabin | | | | | | | | |
| 2007 Sabin | Disease rating | | 0.48 | 0.39 | -0.47 | -0.49 | - - - - | - - - - |
| | Respiration rate 30 DAH | 0.61 | | 0.82 | -0.53 | -0.58 | - - - - | - - - - |
| | 90 DAH | 0.70 | 0.57 | | -0.55 | -0.64 | - - - - | - - - - |
| | Sucrose | -0.80 | -0.58 | -0.67 | | 0.98 | - - - - | - - - - |
| | Extractable sucrose | - 0.82 | -0.59 | -0.68 | 0.99 | | - - - - | - - - - |
| | Glucose | 0.28 | (0.21) | (0.19) | (-0.20) | (-0.20) | | - - - - |
| | Fructose | 0.29 | 0.38 | 0.54 | -0.33 | -0.35 | (0.07) | |
| 2007 Moorhead | | | | | | | | |
| 2008 Moorhead | Disease rating | | 0.68 | 0.64 | -0.62 | -0.63 | 0.40 | 0.64 |
| | Respiration rate 30 DAH | 0.54 | | 0.82 | -0.71 | -0.72 | 0.37 | 0.66 |
| | 90 DAH | 0.51 | 0.82 | | -0.84 | -0.85 | 0.47 | 0.80 |
| | Sucrose | -0.57 | -0.65 | -0.61 | | 0.98 | -0.41 | -0.75 |
| | Extractable sucrose | -0.61 | -0.68 | -0.60 | 0.97 | | -0.41 | -0.76 |
| | Glucose | 0.44 | 0.71 | 0.68 | -0.60 | -0.61 | | 0.67 |
| | Fructose | 0.37 | 0.75 | 0.64 | -0.61 | -0.61 | 0.73 | |

[†] Coefficients in parentheses are not significant at P = 0.05. 2006, n=72; 2007, n=78, and 2008, n=60.

**Table 5.** Differences in disease rating and respiration rate 30 DAH, and respiration rate, sucrose, extractable sucrose, and invert sugar concentrations 90 DAH, between the average of the four sugarbeet hybrids with lowest disease rating and the average of the four hybrids with highest disease ratings, Sabin MN 2006 and 2007 and Moorhead MN 2007 and 2008[†].

| | Disease rating | Respiration rate (mg CO2 kg-1 h-1) | | Extractable Sucrose | sucrose | Glucose | Fructose | Invert |
|---|---|---|---|---|---|---|---|---|
| Year / Location | (0 – 9) | 30 DAH | 90 DAH | (kg Mg-1) | | g /100g sucrose | | |
| 2006 Sabin | -2.3 (0.2)[‡] | -1.54 (0.27) | -2.21(0.42) | 28 (4) | 31 (4) | - - - - - | - - - - - | - - - - - |
| 2007 Sabin | -2.0 (0.2) | -0.85 (0.17) | -1.36 (0.21) | 23 (2) | 25 (2) | -0.40 (ns)[§] | -0.26 (0.11) | -0.66 (0.23) |
| 2007 Moorhead | -2.7 (0.2) | -2.28 (0.34) | -3.35 (0.41) | 19 (4) | 22 (4) | -1.34 (0.41) | -1.39 (0.20) | -2.73 (0.52) |
| 2008 Moorhead | -5.1 (0.2) | -1.74 (0.41) | -2.53 (0.63) | 20 (4) | 25 (4) | -1.79 (0.65) | -0.40 (ns)[§] | -2.20 (0.90) |

[†] Difference = The average of the four hybrids in the trial with the lowest disease rating minus the average of the four hybrids in the trial with the highest disease rating. Rated on a 1 – 9 scale (1 = a full stand of healthy plants to 9 = all or most plants dead).

[‡] Values in parenthesis are standard errors.

[§] All differences, except for glucose at Sabin in 2007 and fructose at Moorhead in 2008, were significant at $P < 0.10$ (and $P < 0.05$).

rates of hybrids with low disease ratings in each environment (Table 3) indicated that respiration rates of hybrids with relatively low disease ratings did not increase over time. The slope of the regression line for respiration rates 90 DAH (Fig. 2B) was twice the slope for respiration rates 30 DAH (Fig. 2A), indicating that respiration differences between relatively healthy roots and roots with high disease ratings increased over time. Accompanying each 2.6 increase in the disease rating scale was an extractable sucrose decrease of 10 kg $Mg^{-1}$ (Fig. 2C), 90 DAH. For each 2.0 increase in the disease rating, invert sugar concentration increased by 1.0 g/100 g sucrose (Fig. 2D). The increase in invert sugar concentration associated with increases in disease severity presumably will increase evaporator scaling in the factory and lead to the formation of compounds that add color to the sugar produced (Dutton and Huijbregts, 2006).

## DISCUSSION

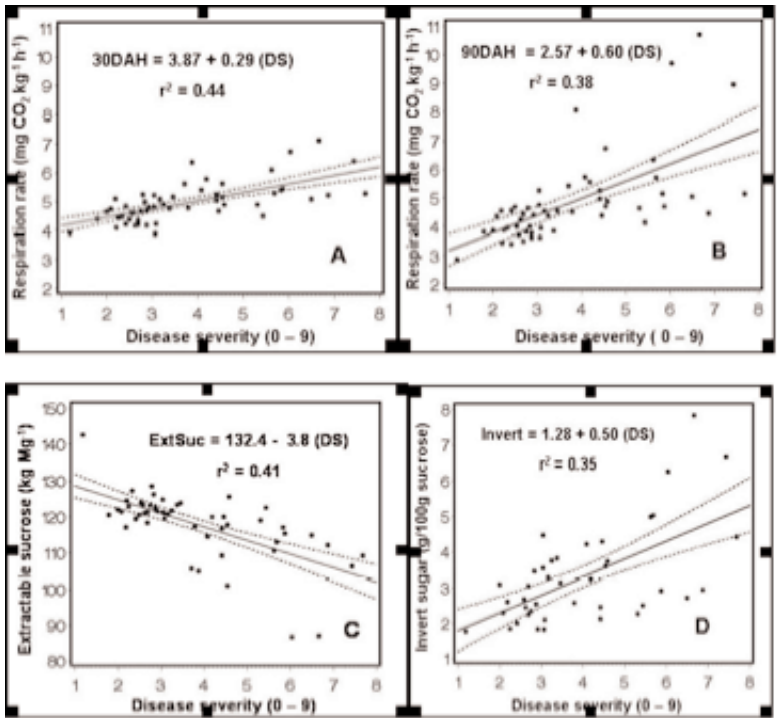
Quantifying relationships between disease severity and sucrose extractability and invert sugar concentration (Fig. 2C & 2D) allows processors to anticipate processing inefficiencies and losses when diseased roots must be stored prior to processing. The regression lines (Fig. 2) and corresponding confidence intervals for the means provide helpful estimates for processors dealing with diseased roots from multiple fields. The magnitude of the coefficients of determination ($r^2$) and the scatter of points around the regression lines suggest that predicting storage losses of roots of a single hybrid from a single field, based upon foliar disease symptoms, will be problematic. Some of the variation around the regression lines, especially for hybrids with intermediate to high disease ratings, may be due to the presence of *Fusarium* species that produce foliar symptoms similar to those caused by *F. oxysporum* but with less vascular discoloration (Hanson and Jacobsen, 2006). As with Aphanomyces root rot and rhizomania (Campbell and Klotz, 2006b; Campbell et al., 2008), data indicate that roots with intermediate or severe Fusarium yellows should be segregated at harvest and processed soon after harvest, if feasible. If timely processing is not possible, abandoning fields with the most severe symptoms prior to harvest should be considered.

The storage samples upon which the relationships noted in this report are based were stored in a refrigerated room with fans for circulation. These storage conditions would minimize contrasts between healthy and diseased roots to the extent they prevent the temperature increase generally associated with elevated respiration rates in storage piles. In a storage pile where healthy and diseased roots are mixed, the temperature increase due to the presence of diseased roots would increase respiration rates in surrounding healthy roots (Dilley et al., 1970). The magnitude of the detrimental effects of diseased roots on nearby healthy roots would depend on how much heat is dis-

sipated from the pile. Furthermore, determining sucrose loss by comparing sucrose concentrations measured at different times during storage underestimates actual losses, since sucrose concentration is calculated on a unit mass basis and a reduction in sucrose content causes an associated decrease in root weight.

Widespread planting of rhizomania resistant hybrids provided a straight- forward method of preventing storage losses due to rhizomania (4). Rhizomania resistance is simply inherited so hybrids can be readily classified as resistant or susceptible. A second-order equation described the relationship between sucrose loss during storage

**Fig. 2.** Regression of postharvest respiration rate of sugarbeet roots 30 (A) and 90 (B) days after harvest (DAH), extractable sucrose concentration (C), and invert sugar concentration (D) 90 DAH on Fusarium yellows severity (rated on a 1 – 9 scale of foliar symptoms where 1 = a full stand of healthy plants and 9 = all or most plants dead). Dashed lines indicate 90% confidence interval for the mean. Respiration rate and extractable sucrose measurements are based upon roots from Sabin, MN, 2006 and 2007 and Moorhead, MN, 2007 and 2008 (n=53). Invert sugar samples were from Sabin, 2007 and Moorhead, 2007 and 2008 trials (n=41).



and Aphanomyces severity (Campbell and Klotz, 2006b; Klotz and Campbell, 2009). Identifying an Aphanomyces severity beyond which respiration rates and sucrose losses rapidly accelerated provided agriculturalists and processors an approximate disease severity level for determining when fields should be abandoned (Campbell and Klotz, 2006b; Klotz and Campbell, 2009). The absence of distinct Fusarium yellows resistance categories among the hybrids examined (Tables 1 & 3) and the linear relationship between Fusarium yellows severity and extractable sucrose and invert sugar concentration complicates hybrid selection for growers and prohibits the ascertainment of a specific disease severity that would warrant abandoning a field. Hybrid by *F. oxysporum* isolate or *Fusarium* species interactions observed in some assessments of Fusarium-yellows resistance (Hanson, 2007; Hanson, 2009; Rivera et al., 2008; Ruppel, 1991) suggests that isolates and species also may differ in their impact on postharvest storage characteristics.

In conclusion, the increase in sucrose loss during storage and the decrease in processing efficiency associated with severity of Fusarium yellows caused by several *Fusarium* species can have substantial economic impact. These losses accelerate over time in storage, so diseased roots should be processed as soon after harvest as possible. Processors should base decisions to abandon diseased fields upon the severity and extent of Fusarium yellows, the prevalence of other diseases that may also increase storage losses, anticipated losses based upon information in this report, past experience, and their ability to segregate and process the more severely impacted roots in a timely manner. The differences in resistance to Fusarium yellows among hybrids are significant and planting available resistant hybrids is an effective means of reducing both preharvest and postharvest losses. A better understanding of prominence and virulence of the various species and strains of *Fusarium* on disease severity and subsequent storage deterioration would assist plant breeders in developing resistant parental lines, sugar companies in evaluating hybrids, and agriculturalists in recommending hybrids for specific areas.

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