Interaction of Sugar Beet Host Resistance and *Rhizoctonia solani* AG-2-2 IIIB Strains

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Abstract

Strausbaugh, C. A., Eujayl, I. A., and Panella, L. W. 2013. Interaction of sugar beet host resistance and *Rhizoctonia solani* AG-2-2 IIIB strains. Plant Dis. 97:1175-1180.

Rhizoctonia crown and root rot caused by *Rhizoctonia solani* can cause serious economic losses in sugar beet fields. Preliminary evidence suggests that there could be interactions between different strains and resistance sources. Thus, field studies were conducted to determine whether nine *R. solani* AG-2-2 IIIB strains varied for virulence when compared with a noninoculated check and interacted with five sugar beet lines (four resistant lines and a susceptible check). The studies were arranged in a randomized complete block design with six replications. Roots were evaluated for surface rot and internal fungal and bacterial rot in September. All strains were virulent on the susceptible check, FC901/C817, and had a similar ranking (r = 0.80 to 0.97; P = 0.0096 to <0.0001) regardless of disease variable. Line FC709-2 was resistant (response not different from noninoculated check, $P \geq 0.1042$) to all strains, while the strain responses resulted in weak interactions with less-resistant lines in 14 of 19 variable-year combinations. Because most commercial sugar beet cultivars contain low to intermediate resistance to Rhizoctonia crown and root rot, the strain used to screen should be considered in order to maintain consistent responses between nurseries and commercial fields.

Rhizoctonia crown and root rot caused by *Rhizoctonia solani* Kühn can lead to yield losses of 50% or more in commercial sugar beet (*Beta vulgaris* L.) fields, affect sucrose losses in stored roots, and lead to difficulties in factory processing (6,17,33,36,39). Because *R. solani* strains form a species complex, strains have been further classified into subgroups known as anastomosis groups (AGs) and intraspecific groups (ISGs) (8,11,30). In Idaho, *R. solani* AG-2-2 IIIB is the primary AG and ISG associated with the most damaging rot in mature sugar beet roots (33). Recent Idaho studies have shown that the fungus is primarily limited to damaging the outer 3 to 5% of the root mass, while subsequent bacterial rot led by *Leuconostoc mesenteroides* subsp. *dextranicum* (Beijerinck) Garvie frequently invades the tissue, leading to 70% or more of the root being rotted (31,32,34,35). Because Rhizoctonia crown and root rot appears to be on the increase in a number of growing areas worldwide, developing management options for this disease is an important concern (4,5,10,22).

Management of Rhizoctonia crown and root rot with crop rotation (4,5,9,19,26,28) and fungicide applications (2,17,18,37,41) helps limit problems but unacceptable levels of rot still frequently occur (2). Host resistance would be the most desirable control measure (24), because it tends to be more cost effective than other approaches. However, most commercial cultivars provide only low to intermediate levels of resistance (32). Cultivars with higher levels of resistance often do not have the yield and resistance to other diseases (curly top, Aphanomyces root rot, Fusarium wilt, and Cercospora leaf spot) needed for cultivar approval. A number of germplasm lines with Rhizoctonia crown and root rot resistance have been developed and utilized by commercial seed companies but resistance is quantitatively inherited and associated with yield drag, making cultivar development difficult (13,20,24). Preliminary evidence suggests that the cultivar selection process also may be complicated by strain interactions with resistance in commercial fields and disease screening nurseries (C. A. Strausbaugh, *unpublished data*).

In previous investigations, differences in virulence between *R. solani* AG-2-2 IIIB strains were observed in both greenhouse and field studies (9,31–33,38). Previous studies also suggest that resistance to *R. solani* should be stable across growing areas (3,15,27) but recent observations in Idaho field studies with *R. solani* AG-2-2 IIIB strains and commercial cultivars from different seed companies suggested that an interaction between strains and source of resistance might exist, at least in the presence of the bacterial rot complex (C. A. Strausbaugh, *unpublished data*). To investigate the potential for a resistance by strain interaction in sugar beet, lines with potentially different sources of Rhizoctonia crown and root rot resistance (most likely the sources of resistance for commercial cultivars) were compared versus a diverse set of *R. solani* AG-2-2 IIIB strains (24,33).

Materials and Methods

***Rhizoctonia* inoculum.** The nine *R. solani* AG-2-2 IIIB strains (F30, F36, F321, F503, F508, F517, F521 [this strain's internal transcribed spacer (ITS) region is genetically identical to that for the R9 strain used in the Ft. Collins Rhizoctonia root rot nursery], F548, and F551) used in these studies had been isolated in Idaho or Oregon and characterized previously (33). The strains had been stored on sterile barley (*Hordeum vulgare* L.) kernels at –80°C (29,40). To create inoculum, the strains were first grown on potato dextrose agar (PDA; Becton Dickinson & Co.) amended with streptomycin sulfate (MP Biomedicals, Inc.) at 200 mg/liter for 10 days. Plugs from these plates were used to inoculate sterile barley kernels. Before inoculation, the barley kernels had been soaked in tap water for 24 h, then autoclaved for 1 h at 121°C. The kernels were autoclaved a second time for 1 h the next day. Plugs from the PDA cultures were placed with the barley kernels and incubated in the dark at 21°C for approximately 6 weeks. The kernels were air dried and ground using a Thomas Wiley Laboratory Mill model 4

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Accepted for publication 25 February 2013.

http://dx.doi.org/10.1094/PDIS-11-12-1078-RE

(GMI Inc.) with a 1-mm screen (modified with 5-mm holes drilled into it).

Experimental design. A factorial experiment with five sugar beet lines provided by the United States Department of Agriculture–Agricultural Research Service, Ft. Collins, CO sugar beet program with different levels of host resistance and nine *R. solani* AG-2-2 IIIB strains plus a noninoculated check were compared in field studies. The studies were arranged in a randomized complete block design with six replications. The five sugar beet lines included a susceptible check (FC901/C817) and four lines (FC703, FC708CMS, FC709-2, and FC718) which included potentially different sources of resistance to Rhizoctonia crown and root rot (14,16,23,25). The nine *R. solani* AG-2-2 IIIB strains were selected based on both genetic and virulence diversity from a previous study (33).

Field study: 2010. The 2010 study was conducted in Kimberly, ID in a field previously cropped to dry beans. The field was managed using standard commercial cultural practices as suggested in the grower guide published annually by the Amalgamated Sugar Co, LLC. The field had been disked on 16 March 2010. Fertilizer (N at 33.6 kg/ha and P_2O_5 at 179.3 kg/ha) and the preplant herbicide Ethotron (42% ethofumesate) at 2.33 liters/ha were applied on 7 April and incorporated with a roller harrow. The plots were planted at a density of 352,123 seeds/ha on 3 May as single rows 3 m long and 0.6 m apart and irrigated with solid set handlines. The seed was treated with the insecticide clothianidin (Poncho; Bayer CropScience) at 60 g a.i. per 100,000 seed and the fungicides metalaxyl (Allegence; Bayer CropScience) at 15.6 g a.i. per 100 kg of seed and thiram (Bayer CropScience) at 250 g a.i. per 100 kg of seed to allow good stand establishment and protection against early season pest problems. The plots were thinned at the four-leaf growth stage to 117,374 plants/ha on 12 June. The plants were inoculated by placing 0.6 g of ground barley inoculum in the crown of each plant at the eight-leaf growth stage on 23 June. No soil was pushed into the crown by cultivation following inoculation but the irrigation scheduled for this week did occur 2 h after inoculation. The field was sprayed with the insecticide Lorsban 4E (44.9% chlorpyrifos; Dow AgroSciences LLC) on 7 July at 1.75 liters/ha to limit pest (leafminers, beet leafhoppers, and aphids) development. Weeds during the growing season were managed using cultivation (done at a 3 kph so as to minimize pushing soil in the crown), because the FC lines were not glyphosate resistant. The cultivation was supplemented by hand weeding to ensure weed-free plots. No root or foliar diseases or pests were evident at the time of root evaluation other than the *Rhizoctonia*–bacterial root rot complex. On 14 September, the first 10 plants in the row were dug and evaluated to determine the percentage of root surface discoloration (dry black tissue). The roots were also bisected through the root lesion to establish the percentage of internal root mass involved in fungal (dry black rot) and bacterial root rot (wet rot) (34).

Field study: 2011. The experiment was in repeated in 2011 using the same methods as in the 2010 study. The field was planted on 4 May and inoculated on 23 June (eight-leaf growth stage). Disease evaluations were conducted on 13 September. No root or foliar diseases or pests were evident at the time of root evaluation other than the *Rhizoctonia*–bacterial root rot complex.

Temperature data. Growing degree days (GDD) using a 10°C base were calculated from data collected by the Twin Falls AgriMet station (station code TWFI). The station is located at 42° 32.747′ north 114° 20.762′ west and was within a short distance of the plots in 2010 (1.4 km) and 2011 (1.2 km).

Isolations. To confirm the presence of *R. solani*, isolations from 20 symptomatic roots selected at random (regardless of isolate) from each study (40 roots total) were conducted on PDA amended with streptomycin (200 mg/liter). To confirm the presence of *L. mesenteroides*, isolations from the same 40 roots assayed for *R. solani* were conducted on glucose–yeast extract–peptone agar (glucose, 10.0 g; yeast extract, 5.0 g; peptone, 5.0 g; sodium acetate 2.0 g; Tween 80, 0.25 g; $MgSO_4 \cdot 7H_2O$, 0.2 g; $MnSO_4 \cdot 4H_2O$, 0.01 g; $FeSO_4 \cdot 7H_2O$, 0.01 g; NaCl, 5.0 g; $CaCO_3$, 5.0 g; agar, 20 g; and 1,000 ml of reverse osmosis (RO) water; adjusted to pH 6.8) with bromocresol purple (0.04 g/liter) amended with tetracycline (0.2 mg/liter) and vancomycin (0.03 g/liter) to make it semiselective for *Leuconostoc* spp. (1,7).

Data analysis. The SAS Univariate procedure (version 9.2; SAS Institute Inc.) was used to test for normality and variance was evaluated with Levene's test (HOVTEST = Levene). Data sets were square root transformed prior to analysis of variance but untransformed means are presented in the tables. Analysis of variance was evaluated using the SAS general linear models procedure (Proc GLM). Mean comparisons were conducted using Fisher's protected least significant difference with $\alpha = 0.05$. Spearman's rank correlation coefficient was used to compare strain rankings.

Results

Temperature. For the June–July period, the GDDs (20 year average = 1,017) were 976 and 967 for 2010 and 2011, respectively. Thus, the GDDs were similar during the initial infection period both years. For the August–September period, the GDDs (20 year average = 968) were 944 and 1,085 for 2010 and 2011, respectively. The 2011 growing season ended quite warm, with the 1,085 GDDs being the highest in the last 20 years.

Surface rot. When all FC lines were included in the analysis, experiments were different ($P = 0.0049$); therefore, all lines were evaluated individually (Table 1). With FC901/C817 and FC708CMS, years ($P = 0.1305$ and 0.5456, respectively) and variances ($P = 0.8390$ and 0.3574, respectively) did not differ, and interactions were not significant ($P > 0.3042$ and 0.0605, respectively); therefore, strains were compared across years (Table 1). With the susceptible check line FC901/C817, all strains were virulent (significantly different from the noninoculated check; $P < 0.0001$). Strains F30, F508, F517, and F521 ranked the highest because they led to the most rot on FC901/C817 and were not significantly different from the highest-ranking strain. In 2010, FC709-2 exhibited the most effective resistance, because the strain responses were not different from the noninoculated check. In 2011, FC709-2 was symptomless. Except for FC718 in 2011, symptoms with the other three lines (FC718, FC703, and FC708CMS) varied depending on the *R. solani* strain–year combination, indicating that resistance was weaker than the resistant response to FC709-2. However, the ranking of the strains was similar with the 2010 FC718 data versus the 2010 FC703 ($r = 0.7764$; $P = 0.0139$), FC708CMS ($r = 0.9660$; $P < 0.0001$), and FC901/C817 ($r = 0.7174$; $P = 0.0296$) data sets. Significant strain correlations based on ranking were also evident for the FC708 versus 2010 FC703 ($r = 0.8404$; $P = 0.0046$) and FC901/C817 ($r = 0.6723$; $P = 0.0473$) and 2011 FC703 versus 2010 FC709 ($r = 0.6698$; $P = 0.0484$). *R. solani* was isolated from 38 of 40 roots and a *Leuconostoc* sp. was isolated from 16 of 40 roots (20 roots assayed per year).

Internal fungal rot. When all FC lines were included in the analysis, experiments were different ($P = 0.0070$); therefore, all lines were evaluated individually (Table 2). With FC901/C817, FC709-2, and FC708CMS, years ($P = 0.0793$, 0.1030, and 0.0705, respectively) and variances ($P = 0.8390$, 0.3983, and 0.3938, respectively) did not differ and interactions were not significant ($P \geq 0.2535$, 0.0939, and 0.0647, respectively); therefore, strains were compared across years (Table 2). With the susceptible check line FC901/C817, all strains were virulent (significantly different from check), except for F36. Five strains (F30, F321, F508, F517, and F521) ranked the highest because they led to the most rot on FC901/C817 and were not significantly different from the highest-ranking strain. FC709-2 exhibited the most effective resistance, because the strain responses were not different from the noninoculated check both years. In 2011, there were also no strain differences for FC718. In other strain–year combinations, more symptoms were observed, indicating that resistance was weaker. However, the ranking of the strains was similar with the 2010 FC718 data versus the 2010 FC703 ($r = 0.8151$; $P = 0.0074$),

FC708CMS (r = 0.8950; P = 0.0011), and FC901/C817 (r = 0.7470; P = 0.0207) data sets. Significant strain correlations based on ranking were also evident for the 2011 FC718 versus 2011 FC703 (r = 0.8016; P = 0.0094) and 2010 FC703 versus FC708 (r = 0.7227; P = 0.0278) and FC709 (r = 0.8371; P = 0.0049).

Internal bacterial rot. When all FC lines were included in the analysis, there was a line–strain interaction ($P < 0.0001$); therefore, all lines were evaluated individually (Table 3). With FC901/C817, FC709-2, FC703, and FC718, years (P = 0.1769, 0.6784, 0.3225, and 0.0630, respectively) and variances (P = 0.0626, 0.3707, 0.8960, and 0.1420, respectively) did not differ and interactions were not significant ($P \geq 0.4994$, 0.4518, 0.1324, and 0.1422, respectively); therefore, strains were compared across years (Table 3). With the susceptible check line FC901/C817, all strains were virulent, except for F36, which was not significantly different from the check. FC709-2 and FC718 exhibited the best resistance, because the strain responses were not different from the noninoculated check both years. In 2011 with FC708CMS, strains also were not different from the noninoculated check. In other strain–year combinations, more symptoms were observed, indicating that resistance was weaker than the resistant response to FC709-2 and FC718. However, the ranking of the strains was similar with the 2011 FC708 data versus the FC703 (r = 0.7000; P = 0.0358) and FC901/C817 (r = 0.7000; P = 0.0358) data sets. Based on ranking, significant strain correlations were also evident for the 2010 FC708 versus FC718 (r = 0.6979; P = 0.0366).

Total (fungal + bacterial) internal rot. When all FC lines were included in the analysis, there was a line–strain interaction ($P < 0.0001$); therefore, all lines were evaluated individually (Table 4). With FC901/C817, FC709-2, and FC708CMS, years (P = 0.4015, 0.2206, and 0.2103, respectively) and variances (P = 0.1088, 0.4858, and 0.2089, respectively) did not differ and interactions were not significant ($P \geq 0.5160$, 0.1897, and 0.1092, respectively); therefore, strains were compared across years (Table 4). With the susceptible check line FC901/C817, all strains were virulent except for F36, which was not significantly different from the

Table 1. Percentage of root surface with dry black discoloration on five sugar beet lines infected by inoculating with one of nine strains of *Rhizoctonia solani* AG-2-2 IIIB in Kimberly, ID 2010 and 2011 field studies

	Sugar beet lines[y]							
	FC718		FC703		FC708CMS	FC709-2		FC901/C817
Strains[z]	2010	2011	2010	2011	2010 and 2011	2010	2011	2010 and 2011
F508	6 b	1	3 cd	1 bc	6 c	1	0	53 a
F30	17 a	4	13 ab	11 a	16 a	3	0	45 ab
F521	17 a	0	15 a	2 bc	13 ab	4	0	44 a-c
F517	6 b	1	14 ab	2 bc	7 c	3	0	40 a-d
F321	16 a	0	16 a	0 c	11 a-c	2	0	32 b-d
F551	8 ab	0	12 ab	2 bc	7 bc	3	0	29 b-d
F503	5 b	1	9 bc	3 b	6 c	3	0	24 c-e
F548	5 b	2	5 cd	2 bc	4 cd	2	0	22 de
F36	0 c	0	2 cd	1 bc	1 de	2	0	11 e
Check	0 c	0	0 d	0 c	0 e	0	0	0 f
$P > F$	<0.0001	0.1313	<0.0001	<0.0001	<0.0001	0.3525	NA	<0.0001

[y] FC designations are for the different sugar beet germplasm lines registered by the United States Department of Agriculture–Agricultural Research Service Ft. Collins, CO sugar beet program. Means within a column followed by the same letter did not differ significantly based on Fisher's protected least significant difference value (α = 0.05). NA = no analysis. Datasets were square root transformed prior to analysis but the untransformed means are presented. When all FC lines were included in the analysis, experiments were different (P = 0.0163). With FC718, years differed (P = 0.0011). With FC703, years differed (P = 0.0097). With FC708CMS, years (P = 0.5456) and variances (P = 0.3574) did not differ and interactions were not significant ($P > 0.0605$); therefore, isolates were compared across years. With FC709-2, years differed (P = 0.0068). With FC901/C817, years (P = 0.1305) and variances (P = 0.8390) did not differ and interactions were not significant ($P > 0.3042$); therefore, isolates were compared across years.

[z] Strains of *Rhizoctonia solani* AG-2-2 IIIB. Check = noninoculated check. $P > F$ was the probability associated with the F value.

Table 2. Percentage of internal root mass with dry black fungal rot on five sugar beet lines infected by inoculating with one of nine strains of *Rhizoctonia solani* AG-2-2 IIIB in Kimberly, ID 2010 and 2011 field studies

	Sugar beet lines[y]						
	FC718		FC703		FC708CMS	FC709-2	FC901/C817
Strains[z]	2010	2011	2010	2011	2010 and 2011	2010 and 2011	2010 and 2011
F508	0.8 de	0.1	1.0 b-e	0.4 bc	0.7 c-e	0.1	6.7 a
F521	3.3 a	0.1	2.2 a	0.4 b	1.6 a-c	0.4	5.7 ab
F30	1.9 a-c	0.5	2.3 a	1.3 a	1.9 a	0.4	5.6 a-c
F517	0.9 cd	0.1	2.1 a-c	0.3 bc	0.7 de	0.3	5.3 a-c
F321	2.5 ab	0.0	1.9 a-c	0.0 c	1.8 ab	0.2	5.2 a-d
F551	1.3 b-d	0.0	1.9 a-c	0.2 bc	1.3 a-d	1.0	3.7 b-d
F548	0.8 de	0.2	0.8 c-e	0.3 bc	0.8 cd	0.1	3.1 c-e
F503	1.1 cd	0.1	1.3 b-d	0.4 b	0.9 b-d	0.2	2.8 de
F36	0.1 ef	0.0	0.3 de	0.1 bc	0.2 ef	0.1	1.4 ef
Check	0.0 f	0.0	0.0 e	0.0 c	0.0 f	0.0	0.0 f
$P > F$	<0.0001	0.0607	0.0003	<0.0001	<0.0001	0.1042	0.0001

[y] FC designations are for the different sugar beet germplasm lines registered by the United States Department of Agriculture–Agricultural Research Service Ft. Collins, CO sugar beet program. Means within a column followed by the same letter did not differ significantly based on Fisher's protected least significant difference value (α = 0.05). Datasets were square root transformed prior to analysis but the untransformed means are presented. When all lines were included in the analysis, experiments were different (P = 0.0119). With FC718, years differed (P = 0.0017). With FC703, years differed (P = 0.0097). With FC708CMS, years (P = 0.0705) and variances (P = 0.3938) did not differ and interactions were not significant ($P \geq 0.0647$); therefore, isolates were compared across years. With FC709-2, years (P = 0.1030) and variances (P = 0.3983) did not differ and interactions were not significant ($P \geq 0.0939$); therefore, isolates were compared across years. With FC901/C817, years (P = 0.0793) and variances (P = 0.8390) did not differ and interactions were not significant ($P \geq 0.2535$); therefore, isolates were compared across years.

[z] Strains of *Rhizoctonia solani* AG-2-2 IIIB. Check = noninoculated check. $P > F$ was the probability associated with the F value.

check. FC709-2 exhibited the most effective resistance, because the strain responses were not different from the noninoculated check both years. In 2011, there also were no strain differences for FC718. In other strain–year combinations, more symptoms were observed, indicating that resistance was weaker than the resistant response to FC709-2. However, the ranking of the strains was similar with the 2010 FC718 data versus the 2010 FC703 (r = 0.8333; P = 0.0053) and FC708 (r = 0.9000; P = 0.0009) data sets. A significant strain correlation was also evident between the 2010 FC703 and FC708 (r = 0.8000; P = 0.0096) data sets.

Comparisons across disease variables. The ranking of the strains was similar (r = 0.8000 to 0.9667; P = 0.0096 to < 0.0001) across all four disease variables (surface rot and internal fungal, bacterial, and total rot) with the susceptible check cultivar, FC901/C817. For the FC lines with resistance, the ranking of the strains frequently varied when compared across disease variables. For the ranking of strains with FC718, only 4 of 21 comparisons were significant: total 2011versus surface 2011 (r = 0.7618, P = 0.0171) and fungal 2011 (r = 0.7067, P = 0.0333), and fungal 2010 versus surface 2010 (r = 0.8814, P = 0.0017) and bacterial 2010 and 2011 (r = 0.7185, P = 0.0292). For the ranking of strains with FC703, only 5 of 21 comparisons were significant: surface 2010 versus fungal 2010 (r = 0.8034, P = 0.0091), bacterial 2010 and 2011 (r = 0.8333, P = 0.0053) and total 2010 (r = 0.8333, P = 0.0053); fungal 2010 versus bacterial 2010 and 2011 (r = 0.8619, P = 0.0028); and bacterial 2010 and 2011 versus total 2010 (r = 0.7000, P = 0.0358). For the ranking of strains with FC708CMS, only 3 of 10 comparisons were significant: surface 2010 and 2011 versus fungal 2010 and 2011 (r = 0.7848, P = 0.0122), bacterial 2011 (r = 0.6891, P = 0.0400), and total 2010 and 2011 (r = 0.6891, P = 0.0400). No rank analysis across strains was attempted for FC709-2, because strains were not significantly different from the noninoculated check with all disease variables.

Table 3. Percentage of internal root mass with wet bacterial rot on five sugar beet lines infected by inoculating with one of nine strains of *Rhizoctonia solani* AG-2-2 IIIB in Kimberly, ID 2010 and 2011 field studies

	Sugar beet lines[y]					
	FC718	FC703	FC708CMS		FC709-2	FC901/C817
Strains[z]	2010 and 2011	2010 and 2011	2010	2011	2010 and 2011	2010 and 2011
F508	0.5	0.3 cd	0.1 b	1.6	0.0	34 a
F30	1.1	3.1 a	0.4 b	9.5	0.0	30 ab
F551	0.3	2.0 ab	0.3 b	2.7	0.8	19 ab
F517	0.2	0.6 b-d	0.0 b	1.4	0.0	19 ab
F521	1.7	1.2 a-c	3.3 a	1.3	0.3	18 ab
F321	1.4	1.0 b-d	3.7 a	1.5	0.0	13 bc
F503	0.3	0.5 b-d	0.6 b	2.3	0.0	12 bc
F548	0.8	0.2 cd	0.0 b	0.2	0.0	10 bc
F36	0.0	0.0 d	0.0 b	0.1	0.2	4 cd
Check	0.0	0.0 d	0.0 b	0.0	0.0	0 d
$P > F$	0.1333	0.0012	0.0037	0.1662	0.2949	<0.0001

[y] FC designations are for the different sugar beet germplasm lines registered by the United States Department of Agriculture–Agricultural Research Service Ft. Collins, CO sugar beet program. Means within a column followed by the same letter did not differ significantly based on Fisher's protected least significant difference value (α = 0.05). Datasets were square root transformed prior to analysis but the untransformed means are presented. When all lines were included in the analysis, experiments were different (P = 0.0220). With FC718, years (P = 0.0630) and variances (P = 0.1420) did not differ and interactions were not significant ($P \geq 0.1422$); therefore, isolates were compared across years. With FC703, years (P = 0.3225) and variances (P = 0.8960) did not differ and interactions were not significant ($P \geq 0.1324$); therefore, isolates were compared across years. With FC708CMS, years differed (P = 0.0010). With FC709-2, years (P = 0.6784) and variances (P = 0.3707) did not differ and interactions were not significant ($P \geq 0.4518$); therefore, isolates were compared across years. With FC901/C817, years (P = 0.1769) and variances (P = 0.0626) did not differ and interactions were not significant ($P \geq$ 0.4994); therefore, isolates were compared across years.

[z] Strains of *Rhizoctonia solani* AG-2-2 IIIB. Check = noninoculated check. $P > F$ was the probability associated with the F value.

Table 4. Percentage of internal root mass with fungal and/or bacterial rot on five sugar beet lines infected by inoculating with one of nine strains of *Rhizoctonia solani* AG-2-2 IIIB in Kimberly, ID 2010 and 2011 field studies

	Sugar beet lines[y]						
	FC718		FC703		FC708CMS	FC709-2	FC901/C817
Strains[z]	2010	2011	2010	2011	2010 and 2011	2010 and 2011	2010 and 2011
F508	1.8 c-e	0.1	1.2 cd	0.6 b	1.5 b-d	0.1	40.5 a
F30	3.6 a-c	1.0	3.7 ab	6.2 a	6.8 a	0.4	35.8 ab
F517	1.0 c-e	0.6	3.2 a-c	0.4 b	1.4 cd	0.3	24.5 ab
F521	6.7 a	0.1	4.4 a	0.7 b	4.0 a-c	0.7	23.5 ab
F551	2.0 b-d	0.0	4.3 a	1.7 b	2.8 a-c	1.8	23.1 b
F321	5.4 ab	0.0	3.8 ab	0.0 b	4.5 ab	0.2	18.2 bc
F503	1.7 c-e	0.1	2.0 b-d	0.6 b	2.3 b-d	0.2	14.7 bc
F548	1.1 c-e	1.5	0.8 cd	0.6 b	0.9 cd	0.1	12.9 bc
F36	0.1 de	0.0	0.3 d	0.1 b	0.2 d	0.4	5.6 cd
Check	0.0 e	0.0	0.0 d	0.0 b	0.0 d	0.0	0.4 d
$P > F$	0.0002	0.4413	0.0004	0.0016	0.0010	0.1630	<0.0001

[y] FC designations are for the different sugar beet germplasm lines registered by the United States Department of Agriculture–Agricultural Research Service Ft. Collins, CO sugar beet program. Means within a column followed by the same letter did not differ significantly based on Fisher's protected least significant difference value (α = 0.05). Datasets were square root transformed prior to analysis but the untransformed means are presented. When all lines were included in the analysis, there was a line–strain interaction (P < 0.0001). With FC718, years differed (P = 0.0057). With FC703, years differed (P = 0.0423). With FC708CMS, years (P = 0.2103) and variances (P = 0.2089) did not differ and interactions were not significant ($P \geq 0.1092$); therefore, isolates were compared across years. With FC709-2, years (P = 0.2206) and variances (P = 0.4858) did not differ and interactions were not significant ($P \geq$ 0.1897); therefore, isolates were compared across years. With FC901/C817, years (P = 0.4015) and variances (P = 0.1088) did not differ and interactions were not significant ($P \geq 0.5160$); therefore, isolates were compared across years.

[z] Strains of *Rhizoctonia solani* AG-2-2 IIIB. Check = noninoculated check. $P > F$ was the probability associated with the F value.

Discussion

When comparing nine strains of *R. solani* AG-2-2 IIIB on the susceptible sugar beet line FC901/C817, significant differences in virulence ($P \leq 0.0001$) between strains were evident but their disease responses and ranking ($r = 0.80$ to 0.97) across all four disease variables (surface, fungal, bacterial, and total internal rot) were similar. When comparing these strains against FC lines representing known sources of resistance to Rhizoctonia crown and root rot in mature sugar beet roots, strain ranking based on disease response tended to vary, except for FC709-2, which was resistant (strains were not significantly different from the noninoculated check) to all strains based on all disease variables ($P \geq 0.1042$). With the weaker sources of resistance (FC703, FC708CMS, and FC718), strain differences and interactions were evident. Within a disease variable, strain rankings tended to be similar; however, they tended to differ when compared across variables, which may be related to resistance being controlled by multiple genes (13,20,24). These resistance genes may lead to interactions because some strains may favor one disease variable over another which, in some cases, were related to the presence of the bacterial rot complex. Because most commercial cultivars contain only low to intermediate levels of resistance (32), the strain and disease variable used to assess the cultivars could potentially influence the results.

All four disease variables (surface rot and internal fungal, bacterial, and total rot) allowed for strain separation based on virulence. With the susceptible line FC901/C817, all strains ranked in a similar ($r = 0.80$ to 0.97) order for all four disease variables. Based on surface rot, these same nine strains when evaluated previously in a large greenhouse assay (33) on the susceptible commercial sugar beet 'Monohikari' had a similar ranking ($r = 0.8513$, $P = 0.0036$) when compared with these field data. All these data sets confirm that a considerable range in virulence exists within the *R. solani* AG-2-2 IIIB strains. Previous studies have also demonstrated a range in virulence among *R. solani* AG-2-2 IIIB strains (9,38) but not quite as wide a range as demonstrated in the studies presented here. The widest range in mean values for the strains was with the root surface variable. Thus, root surface has the potential to allow for good separation of fungal strains. In previous studies, the root surface variable also allowed for the best separation of commercial cultivars for disease resistance and has been the most common variable used to assess Rhizoctonia crown and root rot in mature sugar beet roots (6,27,32).

With the susceptible check line (FC901/C817), the percentage of internal root mass associated with fungal rot was 1.4 to 6.7% while the internal root mass associated with bacterial rot was 4 to 34%, depending on the fungal strain. These data mirror and confirm what has been observed previously in commercial fields and other field studies in the Pacific Northwest production area (31,32,35). The rot almost exclusively occurs on the side of the root in both the field and the inoculated roots of these field studies. Even though the plants were inoculated in the crown, the rot almost exclusively occurred on the side of the root. The internal fungal rot was limited to the outer portion of the root right under the root surface, which is in contrast to greenhouse studies (33) and field studies conducted in cooler production areas where fungal rot appears to be more dominant. In the Pacific Northwest, internal fungal rot is limited, because the bacteria appear to stop fungal penetration and wet bacterial-type rot continues the rot advance in the root (31,32,35). Isolations conducted in previous studies suggest that the bacteria and yeast that invade the tissue (21,34) associated with the wet type rot limit *R. solani* growth but, unfortunately, the lactic acid bacteria, particularly *L. mesenteroides*, also lead to root rot (34). Although the *R. solani* appears to be stopped by the bacterial invasion, previous studies show that there is a synergistic interaction between *R. solani* and *L. mesenteroides* that allows more rot to occur compared with when either are present individually (32). Fungi, particularly *Rhizopus* and *Aspergillus* spp., can also invade tissue compromised by *R. solani*, leading to additional rot in both storage (32) and the field (12).

Identifying resistant germplasm lines has been a priority for the sugar beet industry and a number of resistant lines have been developed (24). The lines used in this study represented potentially different genetic sources of resistance identified through these previous efforts (14,16,23,25). Although the germplasm line FC709-2 was developed in Ft. Collins, CO, it was found to be effective (limited both fungal and bacterial rot variables) against all nine strains of *R. solani* AG-2-2 IIIB evaluated. In previous studies, the sources of resistance to Rhizoctonia crown and root rot have held up across a wide range of geographic areas (3,9,15,27).

Disease response was quite predictable on the susceptible check and the highly resistant line FC709-2 regardless of the disease variable used to assess virulence. However, germplasm lines with intermediate levels of resistance led to interactions with strains. Because most commercial cultivars do not possess the level of resistance found in FC709-2 (32), consideration needs to be given to the *R. solani* strain used for screening in disease nurseries. We hope that the full complement of resistance genes found in FC709-2 can be incorporated into commercial cultivars without excessive yield drag, because this resistance appeared to be affective against all strains of *R. solani* AG-2-2 IIIB evaluated in this study.

Acknowledgments

These data support the objectives for the United States Department of Agriculture CRIS projects 5368-21220-003-00D and 5402-21220-007-00D. We thank the Amalgamated Sugar Co., LLC; Beet Sugar Development Foundation; and Snake River sugar beet growers for supporting our research work; and J. Reed, D. Kenney, and T. Brown for their technical support efforts.

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