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Disease reaction to *Rhizoctonia solani* and yield losses in soybean

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ABSTRACT

Seedling blight and root rot caused by *Rhizoctonia solani* are important constraints to the expansion of soybean (*Glycine max*) production in Alberta, Canada. The reaction of 21 soybean genotypes to *R. solani* was assessed in inoculated field trials in Alberta in 2014–2016. Inoculation with *R. solani* resulted in a significant reduction in stand, nodulation and yield and a significant increase in root rot severity for all of the soybean genotypes. The genotype P001T34R had lower reductions in stand establishment compared with NSC Portage RR, TH29002RR, TH27005RR, or LS003R22, and there were inconsistent variations in yield loss among the genotypes in two of the three site-years. No significant variation in disease severity or nodulation was observed among the genotypes. Stability analysis showed the soybean genotypes P001T34R, 23-60RY, NSC VitoRR, and NSC TilstonRR2Y had higher and more stable stand establishment, while 900Y01, 23-60RY, P001T34R and P002T04R had higher and more stable seed yield in comparison with the other genotypes in this study. The study also revealed that *R. solani* caused a loss of 48% in stand establishment and 52% in seed yield. Root rot severity ranged from 0.38–2.36 on a scale of 0-4 among the genotypes, but it was not consistent over the trials. Root rot severity and yield loss increased with increasing inoculum density, while stand establishment, nodulation and seed yield declined. Regression analysis showed that stand establishment, nodulation, and yield were strongly positively correlated, but strongly negatively correlated with root rot severity.

Key Words: Soybean, *Glycine max*, *Rhizoctonia solani*, seedling blight, yield loss, resistance

Introduction

Soybean (*Glycine max* (L.) Merr.) has great potential as an addition to the current crop rotations in the southern areas of the Prairie region of western Canada (i.e., Alberta, Saskatchewan, and Manitoba). In Manitoba, soybean acreage increased from 232,700 ha in 2011 to over 650,000 ha in 2016 (Soy Canada 2017). In southern Alberta, the area seeded to soybean has grown from 2,400 ha in 2010 to 4,050 ha in 2014 (Gabruch and Gietz 2014). Production of this crop is expected to increase further as new cultivars with early maturity and cold tolerance become available (Chang et al. 2015a). Root rot is a common constraint to soybean production, and the occurrence of root rot was documented in all 29 fields that were surveyed in southern Alberta in 2014 and 2016 (Nyandoro et al. 2015; 2017). Root rot of soybean is a disease complex caused by *Fusarium*, *Pythium*, *Phytophthora* and *Rhizoctonia* species (Nyandoro et al. 2017). The disease reduces stand establishment, which allows increased weed competition later in the growing season.

Rhizoctonia solani Kühn (teleomorph: *Thanatephorus cucumeris* (A.B. Frank) Donk) causes seedling blight, including pre- and post-emergence damping-off and root rot of young and adult soybean plants. (Xue et al. 2007; Zhang et al. 2013; Chang et al. 2015b; McLaren et al. 2015). In the United States, rhizoctonia root and hypocotyl rot causes damping-off as well as lesions on hypocotyls and roots of soybean (Wrather 2001). In Ontario, Canada, rhizoctonia root rot ranked fourth among 22 diseases causing losses in soybean during the period from 1994 to 2000 (Anderson and Tenuta 2001).

Rhizoctonia root and hypocotyl rot have been managed primarily with cultural practices and partial protection with fungicides. However, these approaches have been ineffective or not cost-effective (Schmitthenner and Hilty 1962; Schmitthenner 1987). Cultivars with resistance to

root rot offer an alternative method to reduce the impact of the disease in soybean crops. An earlier study concluded that most ancestral soybean lines and commercial soybean cultivars in the United States were susceptible to *R. solani*, while some showed partial resistance (Bradley et al. 2001). In eastern Canada, cultivar resistance to rhizoctonia root rot is not available and disease management is largely dependent on the use of fungicide seed treatments (Xue et al. 2007). Based on the root rot severity on 70 soybean cultivars evaluated for field resistance, only three were resistant to *R. solani* (Zhang et al. 2013). No studies have been done to evaluate the resistance of soybean genotypes against *R. solani* in Alberta agro-systems.

Rhizoctonia solani collected from soybean in the United States belongs to a diverse array of anastomosis groups (AG) (Nelson et al. 1996). Pathogenicity studies indicated that several crops, including sugar beet (*Beta vulgaris* L.), potato (*Solanum tuberosum* L.), and dry bean (*Phaseolis vulgaris* L.), serve as alternative hosts to the AGs pathogenic on soybean (Muyolo et al. 1993). In Alberta, *R. solani* has been associated with root rot on lupin (*Lupinus angustifolius* L.) (Chang et al. 2008; Zhou et al. 2009; Chang et al. 2014b), field pea (*Pisum sativum* L.), faba bean (*Vicia faba* L.) (Chang et al. 2014a), soybean (Chang et al. 2015b), and canola (*Brassica napus* L.) (Hwang et al. 2014). Zhou et al. (2009) evaluated the anastomosis behavior of 74 isolates of *R. solani* from lupin and other crops in Alberta, and identified isolates that belonged to AG-4, AG-2-1, and AG-2-2. In the USA, isolates virulent on soybean belong to AG-2-2, AG-4 and AG-5 (Nelson et al. 1996).

Rhizoctonia root rot of soybean has caused yield losses as high as 45% in the USA (Muyolo et al. 1993). The rhizoctonia and pythium root rot complex caused an estimated combined yield loss of 108,000 t in soybean in Brazil, Canada, Indonesia, and the USA (Wrather et al. 1997). In Brazil, *R. solani* caused pre- and post-emergence damping-off, root and

hypocotyl rot, and foliar blight in soybean, resulting in an estimated yield loss of 31–60% (Fenille et al. 2002). However, no data are available on the extent of losses caused by rhizoctonia root rot of soybean in western Canada. It is critically important to quantify the magnitude and nature of damage due to a disease, in order to determine the need for developing and/or implementing new disease management strategies (Chang et al. 2013). Moreover, understanding the disease-yield relationships is a prerequisite for measuring the agronomic efficacy and economic benefits of the management measures (Schoeny et al. 2001).

The objectives of the current study were to determine the reactions of soybean genotypes to *R. solani* and to estimate the potential for yield loss associated with this disease in Alberta.

Methods

Reaction of Soybean Genotypes to *R. solani*

An aggressive isolate of *R. solani* (AG-4; isolate code CKP-1, collected from chickpea) was grown on autoclaved wheat for 2 wk., dried and ground as inoculum. Seed of 21 soybean genotypes was planted with a push seeder on June 1, 2014, June 9, 2015 and June 3, 2016 at the Crop Diversification Centre South (CDCS), Brooks, AB (50° 33'N, 111°51'W). Each plot consisted of four 6-m rows with 30-cm spacing between rows, a 60-cm spacing between plots and a 2-m tilled buffer between blocks. The plots were seeded at a rate of 80 seeds per row and a depth of 3 cm. The *R. solani* inoculum was added to the soil with the soybean seeds at the time of seeding at a rate of 40 mL per 6-m row along with 2.5 mL per 6-m row of *Bradyrhizobium japonicum* inoculant (Monsanto Canada Inc.). The trials were arranged in a randomized split plot design with inoculated and non-inoculated treatments as the main plots, soybean genotypes as the sub-plots, and four replicates.

Fertilizer (8-24-24) was applied at 75 kg ha⁻¹ before seeding in each year and the plot area was treated with ethalfluralin herbicide (Edge 5G, 22 kg ha⁻¹, Dow AgroSciences, Calgary, AB) prior to the fertilizer treatment. Plots were sprayed with glyphosate (Roundup Transorb HC, 2.5 L ha⁻¹) at 4-5 wk after seeding to control weeds. Plant stand counts were conducted on June 22, 2014, July 15, 2015, and June 28, 2016. Ten plants per plot were uprooted and rated for root rot severity and root nodulation on a 0–4 scale (Hwang 1994) (Fig. 1,) on July 31, 2014, July 16, 2015 and July 4, 2016. Plants were harvested on October 15, 2014, Oct. 9, 2015 and Oct. 22, 2016. The seed from each plot was dried and weighed to determine yield.

Yield Loss Estimation

Field trials were established on a clay-loam soil at CDCS Brooks on May 19, 2016, and at the Crop Diversification Centre North (CDCN), Edmonton (53° 31'N, 113° 21'W) on June 2, 2016. Seedling emergence was counted on June 28, 2016 at CDCS and counted twice on June 21 and July 11, 2016, at CDCN. Root rot severity and root nodulation were assessed on July 4, 2016, at CDCS and on Aug. 9, 2016, at the CDCN. The trials were laid out in a split-plot design with four replications. Two soybean cultivars, Moosomin and Reston RR2Y, were sown in the main plots and four inoculum levels (0, 20, 40, and 60 mL per 6-m row) were assessed in the sub-plots. Each plot consisted of four 6-m-long rows with 30-cm inter-row spacing, 1.2 m between plots, and a 2-m tilled buffer between blocks. Seed of each cultivar was planted about 5 cm deep at a rate of 75 seeds row⁻¹. The inoculum was sown with the seed, plus 2.5 mL per 6-m row of *Bradyrhizobium* inoculant. Before seeding at Brooks, ethalfluralin herbicide (Edge granular, 5%) was incorporated into the soil at a rate of 27.5 kg ha⁻¹ on 15 October, 2015, and fertilizer (8-24-24, 75 kg ha⁻¹) was incorporated into the soil on 06 November, 2015. Seedling emergence, nodulation and root rot symptoms were recorded at 4 wk after seeding and plots were sprayed

with glyphosate as previously described. Reglone (diquat, 200 g L⁻¹, Syngenta, Calgary, AB) was sprayed onto the crop at a rate of 1.7 L ha⁻¹ - 2 wk before harvest to dessicate the crop. No additional fertilizer or dessicant were applied to the trial at CDCN, but the trial was treated with glyphosate (1 L/ha) on June 23, 2016, for weed control. The plots were harvested with a small plot combine on September 7 in Brooks and were hand-harvested in Edmonton on November 10, 2016. The plants were threshed and the seed was dried at 40°C for 6 days and weighed to estimate yield.

Data Analysis

The reaction of 21 soybean genotypes to *R. solani* each year was analyzed with a mixed-model analysis of variance using the Proc Mixed procedure of SAS software (SAS 9.3, 1985, SAS Institute Inc. NC, USA). Genotypes were a fixed factor and replication was a random factor. To compare the relative effects of the *R. solani* inoculum among the genotypes, stand establishment, nodulation and seed yield data were converted to a proportion of the non-inoculated control prior to analysis, using following the formula: $y = 1 - (I/NI) * 100$; where y = % reduction; I = value in the inoculated plot; and NI = value in the non-inoculated plot. Similarly, increase in root rot severity was calculated by subtracting the level of severity associated with background inoculum (in the non-inoculated control plot) from severity in the inoculated plot. The conversion of the data was performed by replication before analysis, and then a least square mean of the four replications was calculated. A macro was used with the analysis of variance to convert means separation output to letter groupings to designate significant differences (Saxton 1998) at $P < 0.05$ according to Tukey-Kramer's Honest Significant Difference method. A GGE biplot analysis

(Yan and Kang 2002) was performed to investigate the stability of seedling establishment, nodulation and yield performance of the soybean genotypes across the trials.

Data from the yield loss study were also analyzed using the Proc Mixed procedure. In the model, soybean cultivar and inoculum density and their interactions were treated as fixed factors and replication and sites were random factors. Simple linear regression analysis was performed to determine the relationships of the inoculum density with seedling emergence, root nodulation, seed yield and root rot severity. Pearson's correlation coefficient analysis was used to measure the degree of association among the response variables: seedling emergence, root nodulation, seed yield and root rot severity.

Results

Weather conditions

In 2014, temperatures were near average to below average for the early summer, while above-average temperatures predominated in late July, mid-August and late September at CDCS, Brooks (Fig. 2). Most of the substantial (>10 mm) rainfall events occurred in mid-June. In 2015, temperatures were more variable, but fluctuated around the long-term average. The early growing season was dry, with substantial rainfall events (>10 mm) occurring in early August, mid-late August and early September. At Brooks in 2016, temperatures fluctuated around the long-term average, and were most variable before early June and after late August. Rainfall occurred frequently, in significant quantities between mid-May and late July. At Edmonton in 2016, temperatures fluctuated near the long-term average, with rainfall events throughout the growing season (Environment Canada).

Reactions of Soybean Genotypes to *R. solani*

Emergence, nodulation and yield were greater and disease severity lower in all three site-years in control plots compared with those inoculated with *R. solani* (Table 1). Preliminary analysis of the data showed that year $\times$ genotype interaction effect was significant for all the response variables, so the genotypes were compared separately by year, considering genotype as a fixed factor and replication as a random factor. Seedling emergence in the 21 soybean genotypes was reduced by 9–70% in 2014, 21–61% in 2015, and 53–87% in 2016 as a result of inoculation with *R. solani* (Table 2). In 2014, three genotypes P001T34R, P002T04R and 24-61RY showed a lower reduction in stand establishment compared with 900Y81, 90M01, TH27005RR, LS003R22, LS005R22, 24-10RY and 23-10RY. In 2015, TilstonRR2Y and P001T34R showed a lower reduction in stand establishment due to *R. solani* compared with TH29002RR and TH27005RR. In 2016, inoculation severely reduced seedling emergence for all of the genotypes. Over the three-year trial, the soybean genotypes P001T34R showed the lowest overall reduction in stand establishment due to inoculation with *R. solani*. Inoculation with *R. solani* reduced stand establishment by an average of 48% across all of the soybean genotypes in the study.

Stability analysis showed that stand establishment of P001T34R, 23-60RY, NSC Vito RR and NSC Tilston RR2Y was closer to the ideal genotype, defined as a genotype that has the highest stand establishment relative to a non-inoculated control, and is absolutely stable across the environments (Yan and Kang 2002). The four genotypes listed above had higher stand establishment compared with the other genotypes (Fig. 3).

Background levels of root rot infection were observed in control treatments of each of the cultivars (Table 1). Root rot severity increase over the non-inoculated control ranged from 0.38–1.54 in 2014, 0.55–1.20 in 2015, and 0.88–2.36 in 2016. However, these differences were not

statistically significant among the genotypes (Table 3). Across all trials and genotypes, the average increase in root rot severity due to *R. solani* was 1.08 on a 0-4 scale.

The reduction in nodulation due to *R. solani* ranged from 25-67% in 2014, 12-75% in 2015, and 23-90% in 2016. However, these differences were not statistically significant among the genotypes (Table 3). Across all trials and genotypes, the reduction in nodulation was 54%. Stability analysis demonstrated that TH29002RR, 900Y01, and, LS 003R22 had the highest stability of nodulation in the study (Fig. 4).

Yield loss differed among the soybean genotypes, and ranged from 36–74% in 2014, 21–49% in 2015 and 40–90% in 2016 (Table 2). In 2014, P001T34R showed a lower reduction in yield due to *R. solani* compared with 900Y81, 90M01, TH29002RR, TH32004R2Y, LS003R22, LS005R22, 24-10RY and 23-10RY. Also, TilstonRR2Y, P002T04R, 900Y01 and 23-60RY showed a lower reduction in yield compared with LS003R22. In 2015, there were no statistically significant differences among the genotypes with regard to reduction in yield. In 2016, NSC Vito RR, P001T34R, and 23-60RY showed a lower reduction in yield due to *R. solani* compared with 900Y61, TH29002RR and TH27005RR. Across trials and genotypes, the mean yield loss from inoculation with *R. solani* was 52%. Stability analysis revealed that yield in cultivars 900Y01, 23-60RY, P001T34R and P002T04R was more stable relative to the other genotypes (Fig. 5).

Yield Loss Estimation

The levels of inoculum differentially affected seedling emergence, nodulation, severity of rhizoctonia root rot and seed yield in 2016. Regression analysis showed a linear decrease in seedling emergence, nodulation and seed yield (Fig. 6 A, B and C) and a linear increase in root rot severity with inoculum density (Fig. 6D). The regression models were: y (Emergence) = -

$0.46x + 35.90$ ($R^2 = 0.82$); y (Nodulation) = $-0.03x + 2.60$ ($R^2 = 0.94$); y (Root rot) = $0.04x + 0.64$ ($R^2 = 0.93$); and y (yield) = $-0.03x + 3.64$ ($R^2 = 0.89$). There was a very strong negative linear correlation between root rot severity and seedling emergence ($r = -0.97$; $P \leq 0.02$), disease severity and nodulation ($r = -0.99$; $P \leq 0.01$), and disease severity and seed yield ($r = -0.98$; $P \leq 0.01$), and positive linear correlations between seedling emergence and nodulation ($r = 0.94$; $P \leq 0.05$), seedling emergence and seed yield ($r = 0.99$; $P \leq 0.01$), and nodulation and seed yield ($r = 0.95$; $P \leq 0.04$) (Table 4).

Discussion

Seedling blight and root rot caused by *R. solani* have the potential to become important constraints to soybean production in Alberta. In the current study, 21 soybean genotypes were evaluated in inoculated trials under field conditions over three years. Inoculation with *R. solani* caused pre-emergence damping-off and post-emergence seedling blight that reduced stand establishment, nodulation and seed yield, and resulted in root rot symptoms after seedling establishment. Among the soybean genotypes, P001T34R showed the lowest average reduction in stand establishment caused by inoculation with *R. solani*, although statistically significant numerical differences were only observed between this genotype and 900Y81, 90M01, TH27005RR, LS003R22, LS005R22, 24-10RY and 23-10RY in 2014; TH29002RR and TH27005RR, in 2015; none of the genotypes in 2016; and NSC Portage RR, TH29002RR, TH27005RR and LS003R22 over the average of all site-years. Yield loss caused by inoculation with *R. solani* was also lowest for P001T34R in 2014, significantly lower than eight of the other genotypes. In 2016, this genotype had significantly lower yield losses compared with four of the

other genotypes, but there was no significant difference in yield loss among the genotypes in 2015, or when averaged across the site-years.

Rhizoctonia root rot is managed primarily with fungicide seed treatments (Xue et al. 2007), together with cultural practices and biological control. When implemented individually, however, these control practices have limited efficacy (Schmitthenner and Hilty 1962; Schmitthenner 1987). In the United States, most soybean lines were susceptible to *R. solani*, although some showed partial resistance (Bradley et al. 2001). In eastern Canada, only 3 of 70 cultivars exhibited partial resistance to *R. solani* in field trials (Zhang et al. 2013). Use of partially resistant cultivars could improve the efficacy of the other components of an integrated disease management system.

Earlier studies reported a reduction in nodulation and nitrogen fixation in soybean plants under disease pressure from both *R. solani* (Orellana et al. 1976) and other pathogens. For example, inoculation with plant parasitic nematodes severely reduced nodulation and nitrogen fixation (Lehman et al. 1971; Hussey and Barker 1976). Similarly, infection with soybean mosaic virus reduced root nodule weight, nodule efficiency, and leghaemoglobin concentration (Tu et al. 1970). Healthy plants tended to have greater N-fixing capacity than plants infected with *F. oxysporum*, although there was no difference in root nodule fresh weight, leghaemoglobin concentration, or N-fixing efficiency (Corriveau and Carroll 1984). In the current study, nodulation declined with increasing inoculum density, and there was a strong negative association of nodulation with root rot severity. This study showed that rhizoctonia root rot not only reduced stand establishment and seed yield, but also reduced the potential benefits of nitrogen fixation by soybean for the subsequent crops in the rotation. The current study also showed that root nodulation reduction due to *R. solani* varied among soybean genotypes (range

39–62%), although the response among the genotypes was not statistically significant. The variation in root rot severity was not statistically significant among the genotypes in any of the site-years of the study.

Weather conditions had a larger impact on the yield of soybean than is typical for other field crops produced in this region (Chang et al. 2014b). In the inoculated plots, over all genotypes, stand establishment and nodulation were lower than average in 2015, while in 2016, stand establishment, nodulation and yield were much higher than the three-year average and root rot severity was lower (Table 1). On the other hand, the reduction in stand establishment, nodulation and yield and the increase in disease severity due to inoculation with *R. solani* were greater in 2016 than in 2014 or 2015 (Tables 2 and 3), likely due to the higher early-season rainfall in 2016 (Fig. 2). These results indicate that in the effects of disease pressure on seed yield, nodulation and disease severity may be modified by environmental factors, especially those that affect stand establishment.

Estimation of yield loss is important for assessment of disease management strategies. However, very little is known about the effects of *R. solani* on seed yield of soybean. In the current study, a mean yield loss of 52% (ranging from 40–68% for individual lines) resulted from inoculation with *R. solani*. In the yield loss study, increasing inoculation density of *R. solani* reduced stand establishment, root nodulation and yield. Stand establishment, root nodulation, and yield were strongly, positively correlated, and they were strongly negatively correlated with root rot severity. With the intensification of soybean cultivation, the population of *R. solani*, and consequently the severity of root rot can be expected to increase over time.

In summary, inoculation with *R. solani* resulted in large reductions in seedling establishment, nodulation and yield, and regression equations were derived to describe the

impact of infection on seedling establishment, nodulation and subsequent yield reduction. None of the soybean genotypes that were evaluated were resistant to *R. solani*, but the genotypes P001T34R and TilstonRR2Y had the lowest reduction in seedling emergence, and the genotypes P001T34R, 900Y01, 23-60RY, and P002T04R had the lowest reduction in seed yield although there was lack of statistical significance ($P = 0.05$) across the years. These results warrant further research, including evaluation of more soybean accessions.

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Disclaimer

The foregoing is not intended to evaluate or endorse any soybean variety for suitability for cultivation in western Canada.

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Figure captions

Figure 1

Root rot symptoms caused by *Rhizoctonia solani* rated on a 0–4 scale, where: 0 = no disease; 1 = small lesions; 2 = large lesions; 3 = sunken lesion, basal stem girdled; and 4 = cotyledon severed from the coleoptile or the plant is dead (Hwang, 1994).

Figure 2

Summary of temperature and precipitation data from Brooks, Alberta, during the 2014, 2015 and 2016 growing seasons, and from Edmonton, Alberta, in 2016. Long term average temperatures are taken over the periods 1970–1990 and 1994–2014. Data from Environment Canada [Online: climate.weather.gc.ca].

Figure 3

A GGE biplot for stand establishment ranking relative to a non-inoculated control for soybean cultivars inoculated with *Rhizoctonia solani* (2014–2016) in relation to an ideal cultivar (center point of blue circles) with high, stable stand establishment across environments. Cultivars are shown in green font and years in blue. G1 = NSC Portage; G2 = 900Y61; G3 = 900Y71; G4 = 900Y81; G5 = 90M01; G6 = TH29002RR; G7 = TH27005RR; G8 = TH32004 R2Y; G9 = LS003R22; G10 = LS005R22; G11 = NSC Vito RR; G12 = NSC Moosomin RR2Y; G13 = NSC Tilston RR2Y; G14 = P001T34R; G15 = P002T04R; G16 = 900Y01; G17 = 25-10RY; G18 = 24-10RY; G19 = 23-60RY; G20 = 23-10RY; G21 = 24-61RY.

Figure 4

A GGE biplot for nodulation ranking relative to the non-inoculated control for soybean cultivars inoculated with *Rhizoctonia solani* (2014–2016) in relation to an ideal cultivar with high, stable

nodulation across environments. Cultivars are shown in green font and years in blue. G1=NSC Portage; G2=900Y61; G3=900Y71; G4=900Y81; G5=90M01; G6=TH29002RR; G7=TH27005RR; G8=TH32004R2Y; G9=LS003R22; G10=LS005R22; G11=NSC Vito RR; G12=NSC Moosomin RR2Y; G13=NSC Tilston RR2Y; G14=P001T34R; G15=P002T04R; G16=900Y01; G17=25-10RY; G18=24-10RY; G19=23-60RY; G20=23-10RY; G21=24-61RY.

Figure 5

A GGE biplot for seed yield ranking relative to the non-inoculated control for soybean cultivars inoculated with *Rhizoctonia solani* (2014 2016) in relation to the ideal cultivar with high stable yield across environments. Cultivars are shown in green font and years in blue. G1=NSC Portage; G2=900Y61; G3=900Y71; G4=900Y81; G5=90M01; G6=TH29002RR; G7=TH27005 RR; G8=TH32004 R2Y; G9=LS003R22; G10=LS005 R22; G11=NSC Vito RR; G12=NSC Moosomin RR2Y; G13=NSC Tilston RR2Y; G14=P001T34R; G15=P002T04R; G16=900Y01; G17=25-10RY; G18=24-10RY; G19=23-60RY; G20=23-10RY; G21=24-61RY.

Figure 6

Relationship of *Rhizoctonia solani* inoculum density with: A) seedling emergence, B) nodulation, C) root rot severity, and D) seed yield of soybean under field conditions at Brooks and Edmonton, Alberta, in 2016.

Table 1. Effects of inoculation with *Rhizoctonia solani* on emergence, disease severity, nodulation and yield of 21 soybean genotypes at Brooks, AB in 2014, 2015 and 2016.

Treatment	Stand establishment (Plants m ⁻²)				Yield (t ha ⁻¹)			
	2014	2015	2016	Mean	2014	2015	2016	Mean
Inoculated	31.0 ^b	23.1 ^b	34.7 ^b	29.6 ^b	2.18 ^b	2.43 ^b	4.03 ^b	2.88 ^b
Control	49.2 ^a	35.7 ^a	40.7 ^a	41.8 ^a	5.05 ^a	3.30 ^a	4.47 ^a	4.27 ^a

	Root rot severity (0-4)				Nodulation (0-4)			
	2014	2015	2016	Mean	2014	2015	2016	Mean
Inoculated	1.2 ^a	1.1 ^a	0.8 ^a	1.1 ^a	1.2 ^b	0.5 ^b	2.7 ^b	1.4 ^b
Control	0.5 ^b	0.4 ^b	0.1 ^b	0.3 ^b	1.8 ^a	0.8 ^a	3.3 ^a	2.0 ^a

Note: Means in a column and category followed by the same letter do not differ based on the Tukey-Kramer’s Honest Significant Difference test at $P \leq 0.05$. Data are the means of 4 replicates $\times$ 21 soybean genotypes.

Table 2. Reduction of stand establishment and seed yield of 21 soybean genotypes caused by inoculation with *Rhizoctonia solani*, 2014–2016.^a

Genotype code	Genotype	Reduction of stand establishment (%)				Reduction of yield (%)			
		2014	2015	2016	Average	2014	2015	2016	Average
G1	NSC Portage RR	42a-d	53abc	86a	60ab	56abc	49a	79a-d	61a
G2	900Y61	39a-e	30abc	82a	50abc	50abc	26a	89a	55a
G3	900Y71	35b-e	30abc	70a	45abc	53abc	34a	62a-e	50a
G4	900Y81	49abc	40abc	73a	54abc	61ab	37a	75a-e	58a
G5	90M01	47abc	52abc	64a	54abc	74a	33a	59a-e	55a
G6	TH29002RR	44a-d	61a	87a	64ab	67ab	47a	90a	68a
G7	TH27005RR	49abc	56ab	84a	63ab	57abc	46a	87ab	63a
G8	TH32004R2Y	36b-e	36abc	62a	45abc	63ab	32a	58a-e	51a
G9	LS003R22	70a	44abc	84a	66a	75a	36a	78a-d	63a
G10	LS005R22	59ab	30abc	72a	54abc	69ab	39a	69a-e	59a
G11	NSC VitoRR	32b-e	28abc	58a	39abc	55abc	30a	40e	42a
G12	MoosominRR2Y	25cde	33abc	73a	44abc	51abc	25a	63a-e	46a
G13	TilstonRR2Y	29b-e	21c	69a	40abc	47bc	25a	65a-e	46a
G14	P001T34R	14de	21c	59a	31c	36c	21a	46de	34a
G15	P002T04R	14de	34abc	69a	39abc	46bc	32a	51b-e	43a
G16	900Y01	32b-e	39abc	68a	46abc	44bc	29a	84abc	52a
G17	25-10RY	22cde	39abc	66a	42abc	60abc	28a	63a-e	50a
G18	24-10RY	46abc	32abc	71a	50abc	68ab	39a	61a-e	56a
G19	23-60RY	22cde	36abc	53a	37bc	45bc	28a	48cde	40a
G20	23-10RY	57ab	30abc	67a	51abc	66ab	21a	55a-e	47a
G21	24-61RY	9e	37abc	71a	39abc	55abc	21a	61a-e	46a
	Average	37	37	71	48	57	32	66	52

Note: Means in a column and category followed by the same letter do not differ based on the Tukey-Kramer's Honest Significant Difference test at $P \leq 0.05$.

^aData are the % reduction of stand establishment and seed yield in relation to non-inoculated control. Data are the least square means of four replications.

Table 3. Increases of root rot severity and reduction of nodulation on 21 soybean genotypes caused by inoculation with *Rhizoctonia solani*, 2014–2016 (n = 4).^a

Genotype code	Genotype	Increase of root rot severity (0-4)				Reduction of nodulation (%)			
		2014	2015	2016	Average	2014	2015	2016	Average
G1	NSC Portage RR	1.19 ^a	0.55 ^a	0.88 ^a	0.87 ^a	39 ^a	56 ^a	66 ^a	54 ^a
G2	900Y61	0.88 ^a	0.75 ^a	1.44 ^a	1.02 ^a	38 ^a	56 ^a	23 ^a	39 ^a
G3	900Y71	0.73 ^a	0.63 ^a	1.68 ^a	1.01 ^a	37 ^a	31 ^a	90 ^a	53 ^a
G4	900Y81	1.54 ^a	0.65 ^a	1.51 ^a	1.23 ^a	49 ^a	70 ^a	67 ^a	62 ^a
G5	90M01	1.23 ^a	0.55 ^a	1.54 ^a	1.11 ^a	37 ^a	75 ^a	73 ^a	62 ^a
G6	TH29002RR	0.88 ^a	0.58 ^a	1.50 ^a	0.98 ^a	67 ^a	53 ^a	53 ^a	58 ^a
G7	TH27005RR	0.71 ^a	0.92 ^a	1.06 ^a	0.90 ^a	45 ^a	42 ^a	58 ^a	48 ^a
G8	TH32004R2Y	0.79 ^a	0.85 ^a	1.24 ^a	0.96 ^a	64 ^a	12 ^a	60 ^a	45 ^a
G9	LS003R22	0.92 ^a	0.78 ^a	0.93 ^a	0.88 ^a	50 ^a	60 ^a	34 ^a	48 ^a
G10	LS005R22	1.00 ^a	0.63 ^a	0.99 ^a	0.87 ^a	49 ^a	46 ^a	72 ^a	56 ^a
G11	NSC VitoRR	0.77 ^a	1.20 ^a	1.04 ^a	1.00 ^a	54 ^a	31 ^a	87 ^a	57 ^a
G12	MoosominRR2Y	1.04 ^a	0.98 ^a	1.08 ^a	1.03 ^a	48 ^a	45 ^a	71 ^a	55 ^a
G13	TilstonRR2Y	0.85 ^a	0.73 ^a	1.59 ^a	1.06 ^a	61 ^a	65 ^a	71 ^a	66 ^a
G14	P001T34R	1.04 ^a	0.82 ^a	2.16 ^a	1.34 ^a	64 ^a	55 ^a	71 ^a	63 ^a
G15	P002T04R	1.25 ^a	1.16 ^a	2.31 ^a	1.57 ^a	65 ^a	39 ^a	77 ^a	60 ^a
G16	900Y01	1.02 ^a	1.18 ^a	2.16 ^a	1.45 ^a	59 ^a	53 ^a	58 ^a	57 ^a
G17	25-10RY	0.81 ^a	0.90 ^a	1.94 ^a	1.21 ^a	49 ^a	38 ^a	80 ^a	56 ^a
G18	24-10RY	0.71 ^a	0.83 ^a	2.36 ^a	1.30 ^a	26 ^a	48 ^a	75 ^a	50 ^a
G19	23-60RY	0.42 ^a	1.20 ^a	1.94 ^a	1.19 ^a	33 ^a	56 ^a	66 ^a	52 ^a
G20	23-10RY	0.75 ^a	0.60 ^a	1.27 ^a	0.87 ^a	47 ^a	24 ^a	66 ^a	46 ^a
G21	24-61RY	0.38 ^a	0.58 ^a	1.98 ^a	0.98 ^a	25 ^a	55 ^a	65 ^a	48 ^a
	Average	0.90	0.81	1.55	1.08	48	48	66	54

Note: Means in a column and category followed by the same letter do not differ based on the Tukey-Kramer’s Honest Significant Difference test at $P\leq0.05$.

^aData are the increase of root rot severity, and % reduction of nodulation in relation to the non-inoculated control.

Table 4. Correlation among severity of Rhizoctonia root rot, soybean seedling emergence, nodulation, and seed yield under field conditions at Brooks and Edmonton, Alberta, in 2016.

Variables	Severity	Nodulation	Seed yield
Seedling emergence	-0.97*	0.94*	0.99**
Severity		-0.99**	-0.98**
Nodulation			0.95*

Note: *, ** indicate significance at $P \leq 0.05$ and 0.01 , respectively.

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Disease rating scale (0-4)

Fig. 1. Root rot symptoms caused by *Rhizoctonia solani* rated on a 0–4 scale, where: 0 = no disease; 1 = small lesions; 2 = large lesions; 3 = sunken lesion, basal stem girdled; and 4 = cotyledon severed from the coleoptile or the plant is dead (Hwang, 1994).

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Fig. 4. A GGE biplot for nodulation ranking relative to the non-inoculated control for soybean cultivars inoculated with *Rhizoctonia solani* (2014-2016) in relation to an ideal cultivar with high, stable nodulation across environments. Cultivars are shown in green font and years in blue.

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 G16=900Y01; G17=25-10RY; G18=24-10RY; G19=23-60RY; G20=23-10RY; G21=24-61RY.

Fig. 5. A GGE biplot for seed yield ranking relative to the non-inoculated control for soybean cultivars inoculated with *Rhizoctonia solani* (2014-2016) in relation to the ideal cultivar with high stable yield across environments. Cultivars are shown in green font and years in blue.

G1=NSC Portage; G2=900Y61; G3=900Y71; G4=900Y81; G5=90M01; G6=TH29002RR;
 G7=TH27005 RR; G8=TH32004 R2Y; G9=LS003R22; G10=LS005 R22; G11=NSC Vito RR;
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 G16=900Y01; G17=25-10RY; G18=24-10RY; G19=23-60RY; G20=23-10RY; G21=24-61RY.

Fig. 6. Relationship of *Rhizoctonia solani* inoculum density with: A) seedling emergence, B) nodulation, C) root rot severity, and D) seed yield of soybean under field conditions at Brooks and Edmonton, Alberta, in 2016.