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Development of a Greenhouse Assay to Evaluate Potato Germplasm for Susceptibility to Powdery Scab

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Abstract Potato resistance to powdery scab, caused by the protist *Spongospora subterranea* f.sp. *subterranea*, has become extremely important in recent years due to the increased damage caused by this disease. Since field conditions cannot be controlled, they are sometimes sub-optimal for scab susceptibility detection. Thus, a greenhouse assay has been developed that consistently provides optimal conditions so that the susceptibility potential of a clone in the field can be efficiently evaluated. Four potato cultivars were evaluated which varied in levels of powdery scab susceptibility. Two soil types and three inoculum levels were also evaluated. Other factors, such as soil temperature and moisture, were examined to make certain that a range ideal for powdery scab development as reported in current literature was obtained. These greenhouse results were compared with three years of field data collected from trials conducted in the San Luis Valley, Colorado, USA. Each of the cultivars was evaluated for root galling, tuber lesion incidence, and severity. Greenhouse results most consistently matched field results when potatoes were planted in a soil with 50% sand, an inoculum level of one sporeball per gram, and high irrigation coupled with appropriate soil temperatures (ranging from 10–18°C) during the tuber initiation to bulking phase. This soil mix was utilized to test 14 cultivars in the greenhouse with varying levels of resistance to powdery scab. When greenhouse results were correlated with field results a pattern emerged which demonstrated that the cultivars were accurately ranked based on susceptibility to scab (e.g., cultivars with the most resistance to scab in the field also showed the most resistance in the greenhouse). A conversion table using the greenhouse score was developed to estimate the potential susceptibility of a clone under optimum field conditions. Results demonstrate that a greenhouse assay can be successfully used for evaluating advanced potato germplasm for resistance to powdery scab.

Resumen La Resistencia de la papa a la roña polvorienta, causada por la protista *Spongospora subterranea* f. sp. *subterranea*, se ha vuelto extremadamente importante en los años recientes debido al daño en aumento causado por esta enfermedad. Considerando que las condiciones de campo no pueden ser controladas, a veces son sub-óptimas para la detección de la susceptibilidad a la roña. Por lo anterior, se ha desarrollado un ensayo de invernadero que proporciona condiciones óptimas consistentemente, de manera que puede ser evaluada eficientemente la susceptibilidad potencial de un clon en el campo. Se evaluaron cuatro cultivares de papa que variaron en sus niveles de susceptibilidad. También se evaluaron dos tipos de suelo y tres niveles de inoculo. Se examinaron otros factores, tales como temperatura y humedad del suelo, para asegurar que se obtuviera una amplitud ideal de desarrollo de la roña polvorienta como se ha reportado en la literatura actual. Se compararon estos resultados de invernadero con datos de tres años colectados de ensayos desarrollados en el valle de San Luis, Colorado, E.U.A. Cada cultivar se evaluó para agallas de la raíz, incidencia de lesión de tubérculo y severidad. Los resultados de invernadero coincidieron consistentemente en la mayoría de las veces con los de campo cuando las papas se plantaron en un suelo con 50% de arena, y un nivel de inoculo de una bola de esporas por gramo, y riego pesado, acompañado con temperaturas apropiadas del suelo (variando de 10–18°C) durante la fase de iniciación a llenado de tubérculo. Esta mezcla de suelo se utilizó para probar 14 cultivares en el invernadero con variación en los niveles de resistencia a la roña polvorienta. Cuando se correlacionaron los resultados del invernadero con los de campo surgió un patrón que demostró que los cultivares

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fueron clasificados con precisión en su susceptibilidad a la roña (p.e. los cultivares con la mayor resistencia a la roña en el campo también la mostraron en el invernadero). Se desarrolló una tabla de conversión utilizando las calificaciones del invernadero para estimar la susceptibilidad potencial de un clon bajo condiciones óptimas en el campo. Los resultados demuestran que un ensayo de invernadero puede usarse con éxito para la evaluación de germoplasma de papa avanzado para la resistencia a la roña polvorienta.

Keywords Powdery scab · Greenhouse production · Potato resistance · *Solanum tuberosum* · *Spongospora subterranea*

Introduction

Powdery scab, caused by the protist *Spongospora subterranea* (Wallir.) Lagerh. f. sp. *subterranea* Tomlinson (*S. s.s.*), is a disease that affects the roots and tubers of potato plants (*Solanum tuberosum* L.). This pathogen is growing in importance throughout the world and causes scabby lesions on tubers and lesions and galls on roots (Merz and Falloon 2009). Powdery scab is a disease that must be economically and effectively managed because of the large number of potatoes being raised for fresh market consumption. The effective loss of grade from superficial lesions can be a major profit reducer for potato producers.

Control of this disease has been elusive primarily because so few spores are necessary for infection and spore balls can survive for extremely long periods of time in the soil (Wale 2001). For several years, researchers have tried to utilize chemicals for the management of powdery scab. Few have been shown to reduce severity and increase marketable yield. Formalin, copper sulfate, and sulfur were some of the first chemicals used that showed some measure of control. Braithwaite et al. (1994) found that several chemicals (including fluazinam) applied to seed tubers worked well in suppressing the disease. In the San Luis Valley (Colorado), it has been shown that the chemical fluazinam (trade name; Omega) has had some efficacy in controlling powdery scab (Zink et al. 2004). While there have been varying levels of success with different chemicals in different areas of the world during the last 30 to 40 years, it is fairly well documented that most chemicals work best when disease pressure is low (Harrison et al. 1997). A good chemical control has yet to be developed that can control high levels of powdery scab.

Cultural management strategies (e.g., irrigation timing, planting scab free seed into clean, non-infested soils, crop rotation, soil pH manipulation, fertilizer, etc.) have also been evaluated for controlling powdery scab, with little or no success. One important management strategy that could be utilized to control powdery scab is irrigation timing in regions dependent on irrigation, since soil moisture plays a major role in powdery scab development. In a study conducted by Taylor et al. (1986), withholding irrigation during tuber set consistently reduced powdery scab severity, but had little effect on incidence. Also, van de Graaf et al. (2002, 2005) showed that powdery scab is more severe in soils that are kept in constant moisture than in soil where the moisture fluctuates, and that sandy soils were more conducive to powdery scab development than clay soils.

Cultivar resistance is also an important tool available to manage this disease. However, according to Harrison et al. (1997), all potato cultivars are thought to be susceptible to powdery scab to some degree. The current market reliance on cultivars that are highly susceptible to powdery scab is a major factor contributing to the increased difficulties in managing this disease (Christ 2005). Some cultivars are more susceptible to lesion development than to root gall development and vice-versa. It is unclear what regulates the susceptibility in root hairs or on tubers. A cultivar may be resistant to powdery scab lesion development, but be susceptible to root galling. The tubers can appear asymptomatic, while root galls develop on the roots, which results in an increase in the amount of powdery scab inoculum in the soil (Harrison et al. 1997).

In a ten year study conducted by Falloon et al. (2003), 99 potato cultivars were evaluated for resistance. It was found that nearly all of the cultivars that were “very resistant” to lesion development in the field were also resistant to root infection. However, Falloon also indicated that this may not be true in every situation. According to Zink et al. (2004), tuber resistance is not correlated to root resistance. Also, potato cultivars with smooth skin have generally been more susceptible to powdery scab lesion development than cultivars with a russet skin (Miller 2001). There is little known about what causes powdery scab development in different cultivars and what the connection is between lesion and root gall development.

In recent years, more emphasis has been given to breeding new cultivars for disease resistance (Douches 2005). An increasing number of newly-developed potato cultivars are susceptible to the disease (Harrison et al. 1997). Much of this disease screening does not start until late in the breeding process (8th or 9th year) due to restrictions in labor, amount and durability of seed, and time (Holm 2005). As a result, a new cultivar which may be highly susceptible to powdery scab would not be evaluated for resistance until after much time, money, and labor have been put into that cultivar’s development.

In the CSU potato cultivar development program, a greenhouse is used during the initial stages of the development of a new cultivar because the environment can be effectively controlled and maintained with minimal effort (Holm 2005). Several studies have utilized a greenhouse to evaluate *S.s.s.* infectivity and symptom expression (de Boer 1991; Jellis et al. 1987; Merz et al. 2004). Screening cultivars for resistance to powdery scab has primarily been conducted in fields which are infested with the sporeballs of *S.s.s*. Due to the highly sensitive nature of the *S.s.s.* infection process, symptom expression in field environments can be inconsistent from year to year (Falloon et al. 2003). *S.s.s.* prefers low soil temperature and high soil moisture for infection and symptom development (Wale 2001).

In a recent study conducted by Baldwin et al. (2008), a greenhouse assay was used to evaluate cultivar resistance to powdery scab. Although this study provides a good foundation for future powdery scab greenhouse work, other aspects of the powdery scab pathogen need to be examined in order to thoroughly evaluate cultivars for powdery scab resistance. The susceptibility to root gall formation was not evaluated in this study. This needs to be addressed in order to obtain more complete results when comparing with field data and for determining the role of root gall production in soil inoculum dynamics. Also, in order to compare greenhouse with field results, several environmental parameters in the greenhouse need to be evaluated to ensure that the best fit environment will be used for germplasm screening. The combination of parameters yielding results that most closely match field results should then be used in the greenhouse for evaluating powdery scab resistance.

The focus and primary objective of this project was to determine the environmental greenhouse settings which produce results comparable to those found in field trials conducted in the San Luis Valley. A greenhouse assay was developed in which this comparison could be made on a much larger scale. A universal standard could then be developed for powdery scab that is not dependent on disease readings which vary by potato production areas. Also, a potato breeding program could utilize this greenhouse assay to screen new cultivars for powdery scab susceptibility and resistance much earlier in the breeding process. A greenhouse evaluation was chosen for this project to ensure more consistent powdery scab development in susceptible and moderately susceptible potato cultivars and to assist in clearly identifying resistant cultivars.

Once the appropriate greenhouse environmental parameters were identified for powdery scab development, 14 potato cultivars with varying levels of susceptibility were evaluated using this greenhouse assay. Each cultivar was evaluated at harvest for root galling and tuber lesion development. The greenhouse results were then compared with field trial results in order to determine whether using a greenhouse assay could accurately and consistently screen potato cultivars for powdery scab resistance.

Materials and Methods

Acquiring Inoculum and Soil Preparation

Inoculum was obtained from powdery scab lesions on Rio Colorado tubers grown in field plots from the 2005 growing season. Powdery scab lesions were scraped off infected tubers, ground, and the total number of spore balls per gram of inoculum was determined using the methods described by van de Graaf et al. (2005) and Baldwin et al. (2008). On average, 0.001 g of ground material contained 2,725 sporeballs (sb).

Two soil mixes were evaluated (S1=1:1:1 - vermiculite: peat moss: sand, S2=1:1:2 - vermiculite: peat moss: sand). Varying amounts of inoculum were then mixed into each soil type depending on the required inoculum level for each trial. In order to have uniform inoculum addition between the different soil types, an average dry weight (pot size= $15\times15\times15$ cm) was used to determine the amount of inoculum to add to each soil batch, depending on the projected inoculum level (1, 5, or 10 sb/g of soil).

In trial 1, four inoculum levels were evaluated: UC = Untreated Control, I1=1, I2=5 and I3=10 sb/g of soil. For the inoculum source trial (trial 2), Rio Colorado seed with high levels of powdery scab lesions was obtained. The S1 and S2 soil types were used with three inoculum source treatments (untreated control, soil-borne inoculum, and seed-borne inoculum). The average number of lesions per infected tuber eyeball (eye region with one sprout) was between 10 and 15. Each lesion was estimated to have between 400 and 1000 sporeballs (Davidson personal communication) resulting in a total inoculum load of approximately 7500 sb/eyeball. When comparing seedpiece inoculum load to the soil-borne inoculum, it was decided to approximate the levels found on the seedpiece. Thus, 5 sb/g of soil was mixed into the soil to equal approximately 7500 sb/pot. For the soil moisture trial (trial 3) and the cultivar evaluation trial (trial 4), the S2 soil was used and was inoculated with 1 sb/g.

Preparing and Planting Seed

For trials 1, 2, and 3 certified seed potatoes of the cultivars Rio Grande Russet, Russet Burbank, DT6063-1R (Cherry Red), Rio Colorado, and non-certified, scabby Rio Colorado seed were used. For trial 4, the above cultivars in addition to the cultivars Atlantic, Canela Russet, CO94035-15RU, Freedom Russet, Mountain Rose, Purple Majesty, Ranger Russet, Superior, VC0967-2R/Y and VC1002-3W/Y were used. The seed was held at room temperature (20°C) for 21 days to break dormancy and initiate sprouting. A melon scoop was then used to remove individual potato eye regions from the seed tubers. Between tubers, the melon scoop was dipped in a dilute sodium hypochlorite solution (10 ml chlorox + 90 ml sterilized/double distilled water) to reduce disease contamination between sampling. Between sampling each potato cultivar, a fresh batch of the sodium hypochlorite solution was used to disinfect the melon scoop to reduce any disease transfer between cultivars. The potato eyeballs were allowed five to seven days to suberize prior to planting to further reduce the risk of disease development (e.g. seed decay).

Each pot was filled with soil to about 2.5 cm from the top of the pot, to allow a drip tube to fit near the top of each pot (pot size=15×15×15 cm). Each eyeball was then planted 5 cm deep in a soil filled pot. Immediately after planting, each pot was watered to saturation using approximately 500 ml of water.

Irrigation

For trial 1, the pots were irrigated by hand from the planting date until 35 days after planting (DAP). A drip system was installed at 36 DAP, just prior to tuber initiation, to precisely measure the amount of water applied to each pot. On average, the drip system applied water every 1–2 days at approximately 160 ml/pot. After the drip system installation, soil moisture was kept within the 5 to 15 cbar range for the duration of plant growth.

For trial 2, pots were irrigated by hand from the planting date until 35 DAP (crop #1) and 52 DAP (crop #2). At 36 DAP, the drip system was installed for crop #1. Crop #2 had the drip system installed at 53 DAP. Crop #1 averaged one watering event through the drip system every 11/2 days, irrigating an average of 160 ml/pot. Crop #2 was irrigated every 3 days on average, delivering approximately 300 ml/pot. After the drip system installation, soil moisture was kept within the 5 to 15 cbar range.

For trial 3, half of the treatments required an alternate irrigation using either 3.8 l per hour (lph) emitters or 1.9 lph emitters. Pots were watered by hand during the early growth of each crop. At 28 DAP, a drip system was installed for both crops. For crop #1, in the half irrigation regime, the 3.8 lph emitters were exchanged with the 1.9 lph emitters from 46 DAP until 81 DAP when the 3.8 lph emitters were reinstalled. For crop #2, this exchange took place from 49 DAP until 81 DAP. During the growth of both crops, irrigation through the drip system took place every 2 days and the system delivered approximately 260 ml/pot for the 3.8 lph emitter and 100–110 ml/pot for the 1.9 lph emitter. Soil moisture during the drip phase was kept between 5 and 15 cbars for the 3.8 lph pots and between 10 and 25 cbars during the 1.9 lph emitter time frame. The emitter exchange for the half irrigation regime corresponded with the time frame just prior to tuber initiation and through early tuber bulking.

For trial 4, pots were watered by hand during the early growth of each crop. At 28 DAP, a drip system was installed for both crops. During the growth of both crops, irrigation through the drip system took place every 2 days and the system delivered approximately 260 ml/pot. Soil moisture during the drip phase was kept between 5 and 15 cbars.

Managing the Greenhouse Environment

No starter fertilizer was used in any trial; however, each pot was fertilized individually with the same amount of fertilizer. The water soluble fertilizer “Peter’s Blossom Booster” (Earth City, MO) with an analysis of 10:30:20 was used. For all of the trials, the fertility program was started at around 30 DAP and was continued until 95 DAP. Fertilizer was applied (between 200–300 ppm nitrogen per pot) to each pot on a 7 to 10 day schedule during this time frame.

Environmental conditions were controlled in the greenhouse by using an environmental sensor located in each bay which communicated with the Wadsworth Envirostep Control Panel (Arvada, CO). The temperature in the bay was initially set to 18–24°C with a 1.5° differential at 1 DAP for each of the trials. The temperature range was lowered to 11.5–15°C with a 1.5° differential at 36 DAP for the duration of plant growth for trial 1 and trial 2 (both crops) and at 46 DAP for trial 3 (both crops). This moved soil temperatures into a range more favorable for powdery scab development on the roots and on tubers just prior to tuber initiation. Watchdog weather stations (Plainfield, IL) monitored the soil temperatures and soil moisture for all three trials. A Fulex Nicotine Fumigator (Earth City, MO) and Attain (Earth City, MO) was used to help control insect damage on the plants.

Harvesting and Disease Readings (Roots and Tubers)

At approximately 115–120 DAP, all pots were harvested for each of the trials. Tubers were scored for powdery scab severity based on the percent coverage of the tuber by powdery scab lesions. A rating of one to five was given to every tuber that expressed symptoms (Rating: 1 = one lesion up to two percent coverage, 2=2.1 to 5.0 percent, 3=5.1 to 10.0 percent, 4=10.1 to 25 percent, 5 = greater than 25 percent). A severity rating of 5 was the maximum utilized because in a standard commercial operation a rating greater than 5 would be unmarketable. A variation of the powdery scab scoring table developed by Merz (2000) was used to help determine the disease rating for each tuber. The weight of each tuber was determined in order to arrive at the total tuber weight for the scabby and healthy tubers for each plant.

Each symptomatic tuber was rated for severity of the powdery scab symptoms. Then, the total percent of infected tubers per plant was multiplied by the average tuber severity rating per plant to obtain the severity index. The treatment severity index was then calculated by averaging all of the per plant severity indices within a given treatment. This closely approximated the methods used during SLV field trials to calculate severity indices.

Each set of roots was washed with water to remove any excess soil and placed in a zipper seal bag. The roots were weighed (fresh weight) and examined for the presence and severity of root galls using a dissecting microscope. Roots were given a symptom rating of 0–4 based on root gall presence and severity (Rating: 0 = no root galls observed, 1=1 to 3 small or 1 large gall, 2=4 to 10 small or 2 to 3 large galls, 3=11 to 20 small or 4 to 8 large galls, 4=>30 root galls observed).

San Luis Valley Field Trials

Field trials took place over several years in the San Luis Valley, CO in locations which contained naturally infested soil. Sporeball counts were not taken during the field trials, but powdery scab symptoms were prolific in all years on control tubers of susceptible clones/cultivars. All field trials were conducted in cooperating potato growers' fields and production practices (e.g., fertility, planting date, cultivation, harvest) were within normal parameters for potato production in the San Luis Valley.

Statistical Analysis and Experimental Design

A randomized complete block design was used for each greenhouse trial and each trial included 6 replications per treatment. Trial 1 included 4 potato cultivars, 2 soil types, and 4 inoculum levels arranged with a randomized complete block design (RCB) of 4×4×2 factorials. Trial 2 included 2 soil types and 3 inoculum levels with a RCB of 2×3 factorials. Trial 3 included 2 inoculum levels, 2 soil moisture levels, and 4 cultivars arranged with a RCB of 2×2×4 factorials. Trial 4 included 14 different cultivars grown under the same environmental conditions. Trials 2, 3, and 4 were also repeated twice (2 crops) with the same experimental design. The analysis of variance (ANOVA) with least significant difference (LSD) method at a 95% confidence interval was utilized to separate treatment means for each trial. Agricultural Research Management (ARM) revision 6.1.13 fourth edition (Brookings, SD) was the statistical program used for the analysis.

The treatment means for trials 1 and 4 were also compared to three years of field data from the growing seasons 2002–2006, depending on which years the given clones/cultivars were screened in the field. Also, for trial 4, the 14 cultivars were ranked based on root galling and tuber severity index for the two greenhouse crops and for three years of field data. For the greenhouse trials, data from the root gall and tuber severity index readings were subjected to the Friedman non-parametric ranking test with the Proc MIXED model of analysis of variance (SAS® 9.2) in order to rank the cultivars for their level of susceptibility. The root gall and tuber severity index readings for the field trials were subjected to the Proc MIXED model of analysis of variance (SAS® 9.2) without the Friedman test to rank the cultivars under the field conditions. The Friedman test was not performed on the field data due to the expected variability between different years and trial locations. Differences among these cultivars were not analyzed since the primary goal was to determine a possible correlation of disease levels between the greenhouse crops and field trials.

Results and Discussion

Data was collected and analyzed from four separate trials evaluating key environmental factors and cultivars. In trial 1, data was compared to three years of San Luis Valley (SLV) field data for each cultivar to determine which inoculum level and soil type gave results which most closely matched results from the field. In trial 2, inoculum source and soil type were evaluated to determine which source of inoculum produced the most consistent and accurate powdery scab levels. In trial 3, two irrigation regimes were evaluated (high soil moisture level vs. half the soil moisture during the tuber set stage of the potato plant) to determine which regime resulted in the highest and most consistent disease expression. The results from these trials indicated that a soil type with 50% sand, an inoculum level of 1 sb/g of soil (mixed in soil), and a high soil moisture (averaging between 5 to 10 cbars) during and after tuber set produced the most consistent results within a greenhouse when compared to three years of field data. In trial 4, this greenhouse environment was used to evaluate 14 potato cultivars of varying susceptibility for powdery scab severity (root galling & tuber severity index) and the disease results were then compared to three years of field data. A comparative table to match the field readings with the greenhouse readings and provide a relative ranking of resistance was developed.

Trial 1: Inoculum Level x Soil Type

Root Galling

Soil type 1 (S1=33% sand) and soil type 2 (S2=50% sand) gave disease levels which were relatively consistent with each other across all three inoculum levels when evaluating the potato cultivar Rio Grande Russet. However, only the

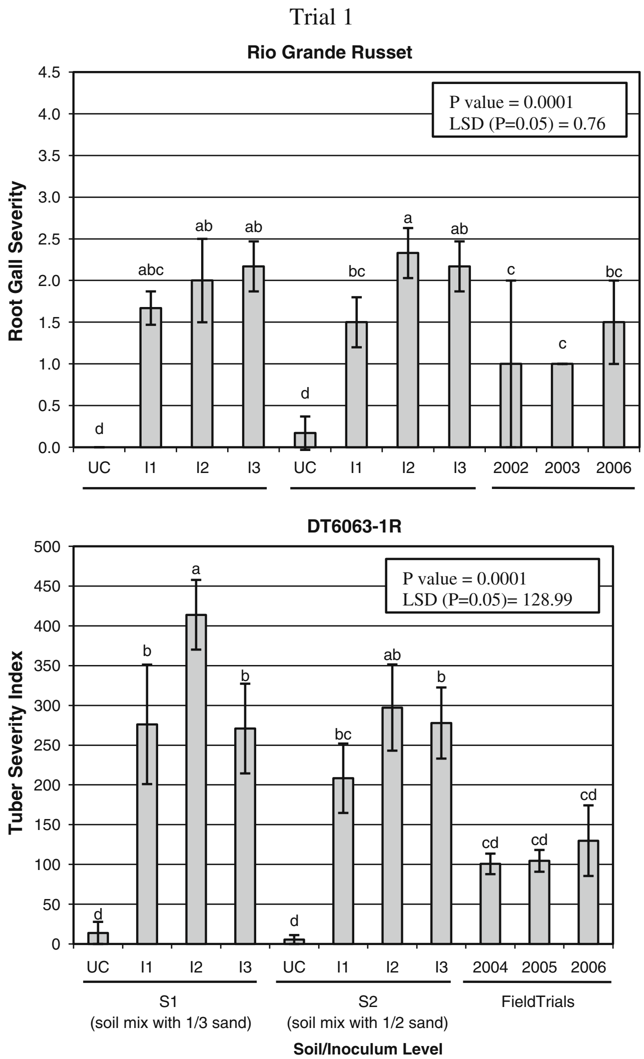


Fig. 1 Evaluation of different soil types and inoculum levels in a greenhouse environment compared with three years of field data for susceptibility to powdery scab root gall formation for the cutivar Rio Grande Russet and tuber severity index for the cultivar DT6063-1R, soil inoculum levels: UC = uninoculated control, I1=1 spore ball (sb)/g of soil, I2=5 sb/g of soil, I3=10 sb/g of soil. Years of field results = 2002, 2003, 2004, 2005, 2006. The data are expressed as means +/− standard error. Means followed by the same letters are not significant at $P=0.05$

1 sb/g inoculum level was not significantly different from the three years of field data for both soil types (Fig. 1).

An inoculum level of 1 sb/g produced root gall results which matched SLV field results most closely for the cultivar Rio Grande Russet. No significant differences were detected between different inoculum levels in the other three cultivars evaluated in the trial (DT6063-1R, Rio Colorado, Russet Burbank)

Severity Index

The tuber severity index for the cultivar DT6063-1R when planted in S2 soil resulted in similar disease readings across all three inoculum levels (Fig. 1). Only the 1 sb/g inoculum level was not significantly different than all three years of field data. Rio Colorado symptoms were not consistent in their differences between inoculum levels and field readings, therefore results from the DT6063-1R were used to determine the appropriate inoculum level. Neither russet cultivar expressed tuber symptoms.

The combination of S2 soil and an inoculum level of 1 sb/g most closely matched SLV field results. S2 soil also produced the most consistent results across the three inoculum levels.

Overall Summary

To justify one soil type/inoculum level over another, all powdery scab symptoms should be evaluated. It should be noted that van de Graaf et al. (2005) found when comparing soil types a soil with higher sand content tended to be more conducive to powdery scab development than less sandy soils when soil moisture was high. This may be due to a large pore size in sandy soils which would allow the *S.s.s.* zoospores to move more freely to infect the host tissue. Also, as higher levels of inoculum (5 and 10 sb/g) were added to the soil, disease levels did not tend to increase. Based on previous research, once the optimum inoculum level is reached, *S.s.s.* infection levels do not increase as inoculum levels are increased (van de Graaf et al. 2000; Lees et al. 2008). The combination of S2 soil at the 1 sb/g inoculum level was determined to be the most appropriate for use in developing the greenhouse assay.

Trial 2: Inoculum Source x Soil Type

Inoculum Source

In trial 2, the variables of inoculum source and soil type were evaluated using the susceptible potato cultivar Rio Colorado. Across both crops and both soil types, the scab infested seed resulted in lower powdery scab severity (root galls and tuber lesions) than clean seed planted in inoculated soil with 5 sb/g (Fig. 2).

Root gall severity was significantly higher in the S2 inoculated soil than in the scab infested seed pots and no difference was observed for the S1 soil in crop 1. For crop 2, the S1 inoculated soil was significantly higher than the scab infested seed pots, with a lower overall severity for the S2 inoculated soil than in crop 1. Overall, the severity index was higher in the plants which started from scab-free seed grown in inoculated soil than in plants started from scab infested seed.

Watering Regime Between Crops

There were distinct differences between the two greenhouse crops in trial 2. Overall, disease levels were higher in crop 1

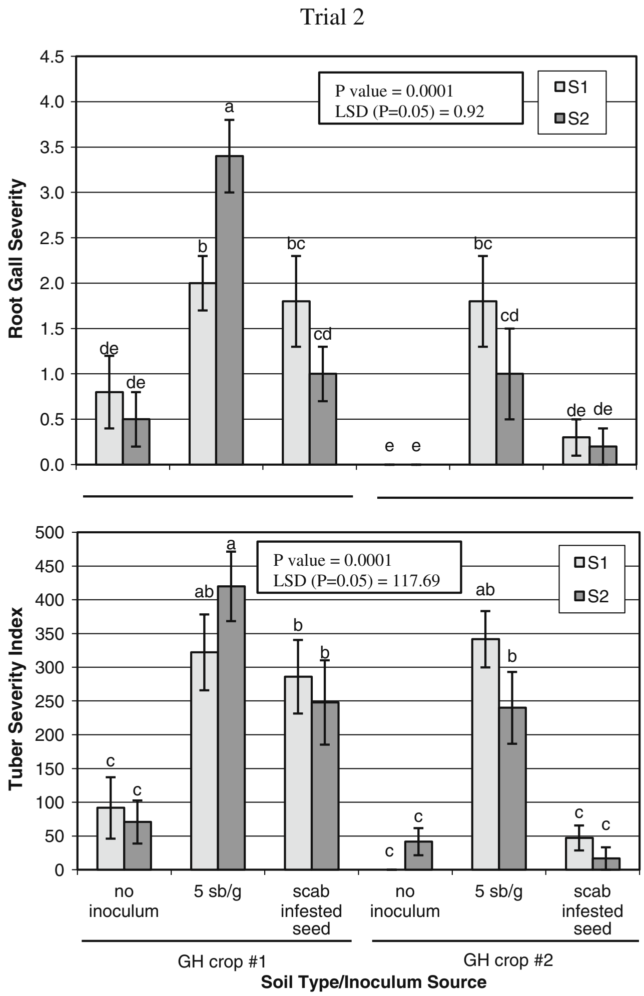


Fig. 2 Evaluating two inoculum sources for powdery scab root gall severity and tuber severity index in a greenhouse for the potato cultivar Rio Colorado. Inoculum Source: two sources were evaluated - 5 sb/g = soil was inoculated with 5 sb/g of soil, scab infested seed = seed with powdery scab lesions. Soil Type: S1=1/3 of soil is sand, S2=1/2 of soil is sand. Data are expressed as means +/− standard error. Means followed by the same letters are not significant at P=0.05

than in crop 2 (Fig. 2). Also, S1 soil produced higher powdery scab disease values than S2 soil for crop 2, but not in crop 1. One possible reason for these differences is the irrigation regime used for each crop. The drip system for both crops was set up with 3.8 lph emitters but the crops were grown nearly a year apart. The water pressure available between crops was different due to differences in the number of treatments being irrigated, which affected total water consumption throughout the greenhouse during the growth and maturing of each crop. The watering regime for crop 1 averaged one irrigation event every two days during and after tuber set, resulting in approximately 160 ml of water per pot per irrigation event. In crop 2, plants were irrigated every 3 days resulting in 300 ml of water per pot per irrigation event. The differences between irrigation regimes more than likely had an effect on disease severity. Both irrigation regimes provided the same total amount of water for each crop; however, the crop 2 regime allowed the soil to dry more between irrigations. This reduction of available free water in the soil should have reduced the number of zoospores infecting both roots and tubers as explanation for the lower disease levels in crop 2 when compared with crop 1.

Based on the data from trial 2, irrigating more per irrigation event but less frequently may have an impact on reducing powdery scab severity in the field. This would have the most impact on disease severity during tuber set since the daughter tubers are most susceptible to *S.s.s.* infections during this stage of tuber development (Wale 2001).

Managing irrigation timings may be a good strategy to utilize for the control of powdery scab. However, due to inconsistencies in the literature, more evaluations of differing irrigation regimes during tuber set needs to be conducted in the San Luis Valley. Evaluation under field conditions and in additional greenhouse trials must occur before recommendations on irrigation timing can be made to potato producers for the management of powdery scab is essential.

Overall Summary

A soil thoroughly mixed with *S.s.s.* inoculum was determined to be a better choice for use in a greenhouse assay than using scab infested seed in un-infested soil in order to obtain accurate disease results. In addition, scab infested seed is not always an option for use in a greenhouse due to the limited availability of this seed in cultivars which are resistant to tuber lesion development (e.g., russets).

Trial 3: Soil Moisture x Inoculum Level

To determine the proper soil moisture level for optimum powdery scab symptom expression, two different irrigation regimes were evaluated. Plants in each regime were irrigated the same number of times with the amount of water per irrigation event differing between the two regimes. This trial was repeated with two crops. According to Harrison et al. (1997), soil moisture plays a key role in the infection of potato roots and tubers by *S.s.s.*

Disease Readings

In the cultivar Rio Colorado, there was no significant difference between the two irrigation regimes in root gall severity, but a significant difference was observed for tuber severity index (Fig. 3). The tuber severity index was significantly higher in the high moisture regime than in the low moisture regime for both crops.

In the cultivar Rio Grande Russet, the high irrigation regime resulted in significantly higher levels of root galling

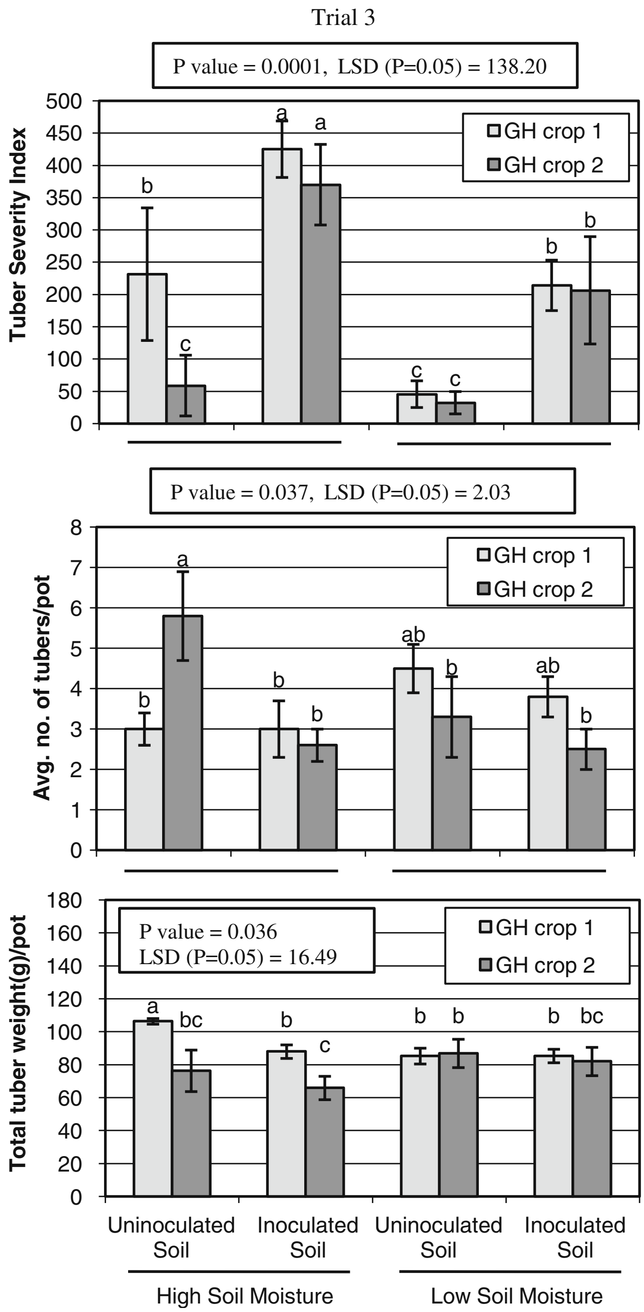


Fig. 3 Evaluating powdery scab tuber severity and plant health using two irrigation regimes in a greenhouse for the potato cultivar Rio Colorado. Inoculated soil=1 sb/g of soil. The data are expressed as means +/− standard error. Means followed by the same letters are not significant at P=0.05

than in the half irrigation regime for crop 1 (Fig. 4). In crop 2, no significant difference was observed between irrigation regimes. Also, no tuber lesions were observed for the cultivar Rio Grande Russet.

The cultivar Rio Grande Russet showed a significant reduction in root gall severity when the half irrigation regime was utilized. The difference in root galling between the two cultivars may have been due to the fact that the water reduction between the two irrigation regimes was insufficient to impact spore germination and root infection for Rio Colorado. Also, Rio Colorado has a higher susceptibility to root galling than Rio Grande Russet, which has been observed to be quite low in field trials. This difference in response to irrigation may provide insight into cultivar variation and resistance.

The cultivars Russet Burbank and DT6063-1R did not show significant differences between irrigation regimes.

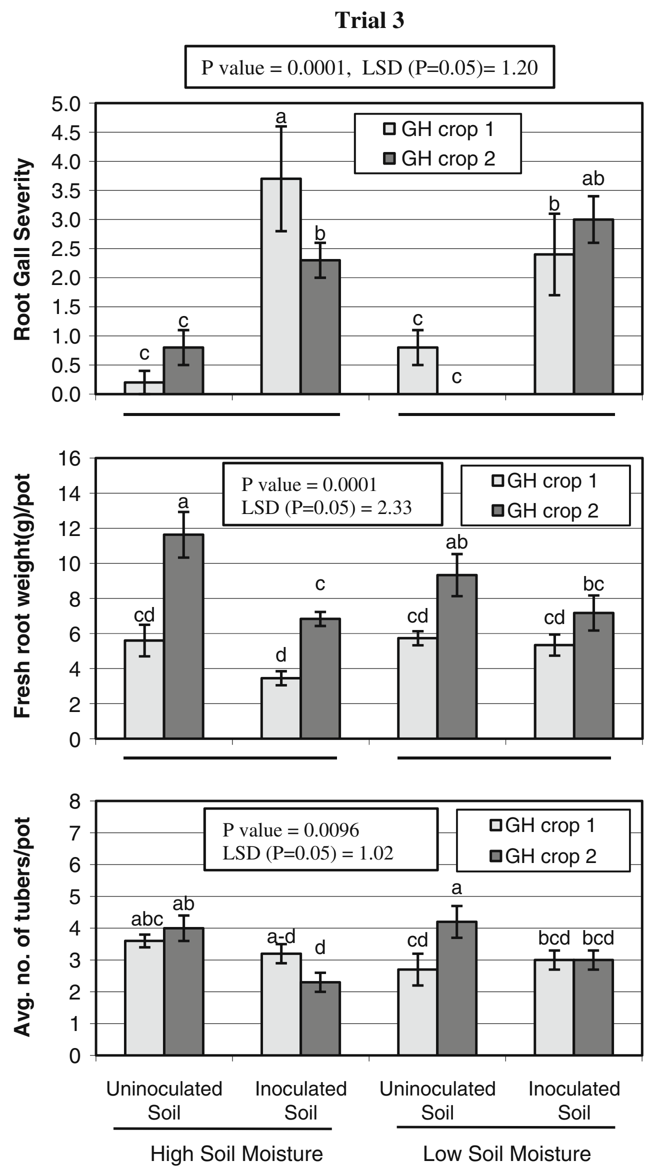


Fig. 4 Evaluating powdery scab root gall severity and plant health using two irrigation regimes in a greenhouse for the potato cultivar Rio Grande Russet. Inoculated soil=1 sb/g of soil. The data are expressed as means +/− standard error. Means followed by the same letters are not significant at P=0.05

Overall Summary

A high soil moisture irrigation regime (<10 cbars) during a potato plant's tuber set stage resulted in significantly higher powdery scab levels (both tuber lesions and root galling) in a greenhouse grown crop than lower soil moisture levels.

A lower soil moisture for the cultivars Rio Colorado and Rio Grande Russet could be reducing the levels of root exudates released into the soil because of a perceived water stress. Some research suggests that plant exudates may be triggering the release of *S.s.s.* zoospores from the sporeball and attracting them to the plant tissue for infection (Harrison et al. 1997). With a potential reduction in exudates, the number of *S.s.s.* infections could be reduced in these cultivars. This would explain the low disease levels found when these cultivars were grown under low soil moisture in trial 3.

A perceived water stress may also trigger a resistance response in the potato cultivars with lower powdery scab severity under the half irrigation regime. This resistance response could also account for lower severity levels. In the case of Rio Grande Russet, the cultivar is known for its deep root system and water scavenging ability within the soil profile (Davidson personal communication). The ability of this cultivar to more fully utilize scarce water may tend to favor the potato over the pathogen in the cycle of spore release, infection, and symptom development. In any case, when looking at screening potato germplasm for susceptibility to powdery scab, the high soil moisture irrigation regime appears to be the most useful for this approach.

Factors Influencing Plant Health

A decrease in potato plant health can result from powdery scab symptom expression in roots and tubers if disease levels are high (Harrison et al. 1997). Therefore, data on fresh root weight, tuber number, and overall tuber weight was collected in addition to disease data for trial 3. A decrease in fresh root weight, tuber number and size was observed in inoculated soil when compared with un-inoculated soil under the high soil moisture irrigation regime. Each cultivar showed a trend towards reduced plant health in at least one of these three areas.

In Rio Colorado, the total tuber number in crop 1 and total tuber weight in crop 2 were significantly lower in the inoculated soil (Fig. 3), but no difference was observed for fresh root weight. In Rio Grande Russet, the fresh root weight and the total tuber number was significantly less when planted in the inoculated soil for crop 2 (Fig. 4), however no difference was observed in tuber number.

In addition to the presence of inoculum in the soil, tuber yield can also be affected by the amount of available water in the soil during tuber set. In the cultivar Rio Colorado, the total number of tubers in un-inoculated soil was significantly less in the lower moisture soils than in the higher moisture soils for crop 1 (Fig. 3). However, this trend was not observed in Rio Grande Russet. For a potato producer, the limiting of irrigation water during tuber set may result in a decrease in powdery scab symptoms in susceptible potato cultivars based on results found in this trial and from Harrison et al. (1997). A downside to this management practice is a possible decrease in tuber yield resulting from limiting the water supply to the potato plant during tuber set, which was observed in this trial for the cultivar Rio Colorado. For this reason, limiting the total amount of water during tuber set is not recommended in all situations as a control measure for powdery scab.

The results from trial 3 indicate that susceptible potato cultivars grown in conditions favorable for adequate powdery scab symptom development tend to decrease root health and overall yield of tubers produced by the plant. This is another disadvantage, in addition to cosmetic tuber damage, for susceptible potato plants grown in conditions favorable for powdery scab development (Harrison et al. 1997).

Trial 4: Cultivar Evaluation

The most appropriate greenhouse conditions determined from trials 1, 2, and 3 were used in trial 4 and were tested using fourteen potato cultivars with varying susceptibility to powdery scab. The results collected from the greenhouse were then compared with known powdery scab results from SLV field trials over several years. For the cultivars evaluated, results from two greenhouse crops resulted in more consistent powdery scab levels than SLV field trial disease levels. Also, powdery scab levels from the greenhouse typically equaled disease levels from the field trial year that had the highest severity when evaluating field trials from three different years. The disease potential for each potato cultivar evaluated in trial 4 was obtained in the greenhouse. Since field trials often result in lower disease levels than the disease potential for each cultivar, the greenhouse is an important tool for determining the highest level of powdery scab a potato cultivar could potentially develop when grown under favorable conditions.

Susceptible Cultivars: (DT6063-1R, Rio Colorado, VC0967-2R/Y, Mountain Rose)

Each of the four red-skinned potato cultivars tested in this trial were chosen because of their high susceptibility to powdery scab root galling and tuber lesion development. When looking at the tuber severity index, there were no significant differences between the two greenhouse crops and the field year with the highest level of disease (Fig. 5; DT6063-1R was not listed in the figure because no significant differences were observed between field and greenhouse results). For the three years of

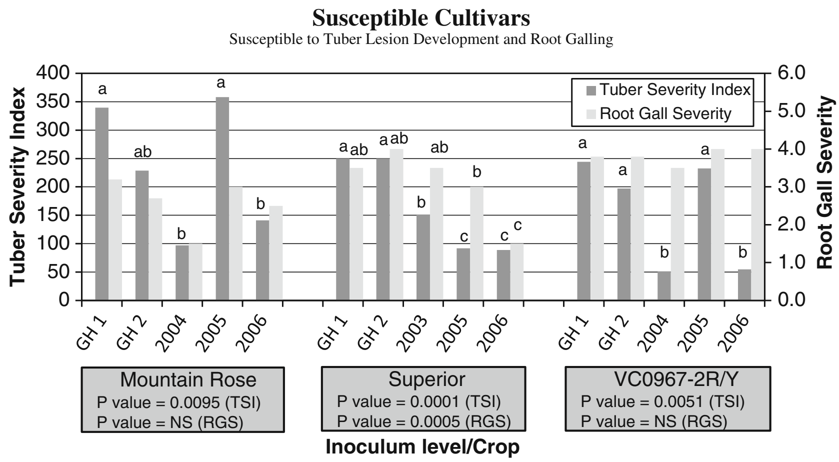


Fig. 5 Evaluation of three potato cultivars which are susceptible to powdery scab, comparison of three years of field data to two greenhouse crops evaluating powdery scab root gall severity and tuber severity index. x-axis: GH 1 & 2 = greenhouse crops 1 & 2; 2003, 2004, 2005, 2006 = yrs of field data. TSI = Tuber Severity Index, RGS = Root Gall Severity. Data was analyzed within each cultivar to determine differences between greenhouse and field trial results. Bars with the same letters are not significant at $P=0.05$ for each cultivar

field data, there were significant differences in tuber severity index indicating that powdery scab severity varies between years when trials are conducted in a field setting. This demonstrates that symptom expression from data collected in greenhouse trials are more consistent than symptom expression obtained from several years of field trials.

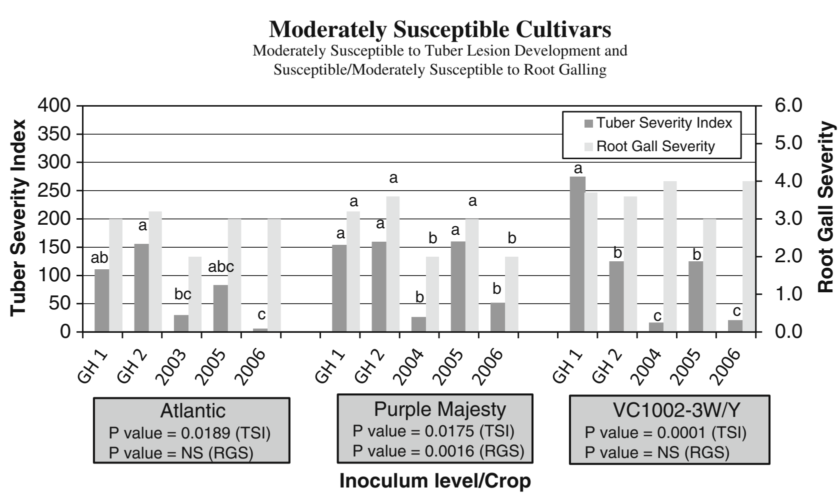
It is important to note that field variation (environment, soil inoculum levels, etc.) can give the impression that a cultivar has powdery scab resistance when indeed it does not. For example, the cultivars Mountain Rose and VC0967-2R/Y demonstrated what appeared to be levels of resistance for tuber symptoms in two out of three years of field testing. If those two years were used to determine resistance, a false impression would be obtained suggesting resistance was present. Using the greenhouse results, however, dispels this impression by demonstrating that both cultivars have much higher tuber susceptibilities. The greenhouse system gives a more realistic scenario for resistance screening.

Moderately Susceptible Cultivars: (Purple Majesty, VC1002-3W/Y, Atlantic, Superior)

Each of these four potato cultivars were tested because of their relatively moderate susceptibility to powdery scab tuber lesion development. Purple Majesty produces tubers with purple skin and VC1002-3W/Y, Atlantic and Superior produce tubers with white skin. Only in the cultivar VC1002-3W/Y were the tuber severity index means significantly different from each other for the two greenhouse crops. Also, when looking at field results, there were high levels of variability between the different years in three of the moderately susceptible cultivars (Fig. 6; Superior was not listed in the figure, but the results were similar to Purple Majesty).

For the potato cultivar VC1002-3W/Y, the three years of field data, in addition to the two greenhouse crops, were variable in tuber severity index. This may be due to a cultivar response to S.s.s. infection, rather than any

Fig. 6 Evaluation of three potato cultivars which are moderately susceptible to powdery scab, comparison of three years of field data to two greenhouse crops evaluating powdery scab tuber severity. x-axis: GH 1 & 2 = greenhouse crops #1 & 2; 2003, 2004, 2005, 2006 = yrs of field data. Data was analyzed within each cultivar to determine differences between greenhouse and field results. Bars with the same letters are not significant at $P=0.05$ for each cultivar



inconsistencies between the environmental parameters in the two greenhouse crops.

Tuber symptom expression for the cultivars of Atlantic and VC1002-3W/Y were higher in the greenhouse than in the field. Greater inoculum uniformity in the greenhouse soil and a small pot size restricting tuber number and size may have caused the increased disease expression in the greenhouse since these conditions are not present in the field.

Cultivars with Low Susceptibility: (Canela Russet, CO94035-15RU, Freedom Russet, Ranger Russet, Rio Grande Russet, Russet Burbank)

Each of these cultivars produce tubers which have russet skin. Potato tubers with a russet skin tend to be resistant to powdery scab tuber lesion development. However, a few powdery scab lesions were observed on tubers with a russet skin in the greenhouse and during field trials (Fig. 7). The levels were typically low and only three of the six cultivars with russet skin expressed any symptoms (Table 3). Due to the low level of tuber lesion development in these cultivars, only root galling data was analyzed (Fig. 8; Canela Russet and Ranger Russet were not listed in the figure, but the results were similar to Rio Grande Russet).

A wide range of variability existed in root gall severity between the three years of field data for each cultivar, except Rio Grande Russet, and no significant variability existed between the two greenhouse crops for root gall severity within cultivars.

For nearly every russet skinned cultivar evaluated in trial 4, the crops grown in the greenhouse tended to equal or have higher levels of disease than the field data from the year with the highest level of disease. The cultivar CO94035-15RU showed that root gall severity levels were lower in greenhouse and field trials than in any other

Fig. 7 Normally resistant, russet cultivars can demonstrates S.s.s. tuber symptoms under favorable soil conditions (cultivar - Russet Norkotah)

cultivar evaluated in trial 4. Based on these results, this cultivar could potentially be used in a breeding program for the development of a potato cultivar which is fully resistant to powdery scab root galling. Results from trial 4 also indicate that a cultivar such as Rio Grande Russet could be used for powdery scab resistance development. Low root galling was present in the field and after adjusting for the differences for field and greenhouse environments, Rio Grande Russet still had a relatively low root gall rating. While Rio Grande Russet may be a good candidate, results indicate that CO94035-15RU would be a better candidate in breeding for powdery scab root galling resistance.

Relative Ranking of Field and Greenhouse

Throughout trial 4 of this project, powdery scab symptom expression was higher in the greenhouse than in the field for nearly every cultivar evaluated. Since disease expression was more consistent in the greenhouse than in the field, it makes sense to use this greenhouse assay rather than field trials to evaluate potato cultivars for powdery scab resistance. However, most potato cultivar evaluations on powdery scab resistance have been conducted using field trials and the greenhouse tends to produce higher disease levels than the field. For researchers to use the results from this greenhouse assay and compare them with known field results, a relative ranking of cultivar susceptibility was established.

To simplify this relative ranking, three levels of powdery scab susceptibility were established - low, medium, and high (Table 1). All fourteen cultivars evaluated in trial 4 of this project have been included in a relative ranking table (Tables 2 and 3). This relative ranking has been developed for root gall severity and tuber severity index. The greenhouse disease values listed in the two tables are the means of both greenhouse crops from trial 4 and the field disease values are the means from several years of SLV field trials. The mean rank estimate obtained from the Friedman test and SAS® Proc MIXED are also included for the greenhouse and field results. Due to the high levels of disease in the greenhouse, cultivars

Table 1 Powdery scab ranking of tuber and root gall severity for field and greenhouse trials based on Friedmans correlation (greenhouse) and proc mixed analysis (field)

	Relative Ranking for Root Gall Severity (maximum rating=4)		Relative Ranking for Tuber Severity (maximum rating=500)	
Disease level	Greenhouse	Field	Greenhouse	Field
Low (L)	0–2.20	0–1.75	0–50.0	0–25.0
Medium (M)	2.21–2.75	1.76–2.50	50.1–225.0	25.1–115.0
High (H)	2.76–4.00	2.51–4.00	225.1–500.0	115.1–500.0

Table 2 Potato cultivars with corresponding root gall severity (average of three years of SLV field results and average of both greenhouse crops – trial 4)

Greenhouse (2 crops)				Field (3years)			
Severity Level	Potato Cultivar	Mean Severity (0–4)	Mean Rank Estimate	Severity Level	Potato Cultivar	Mean Severity (0–4)	Mean Rank Estimate
High	VC0967-2R/Y	3.83	23.17 a	High	VC0967-2R/Y	3.83	74.75 a
	Superior	3.73	22.18 a		VC1002-3W/Y	3.67	71.50 a
	VC1002-3W/Y	3.64	21.50 a		Superior	3.00	55.41 ab
	Purple Majesty	3.36	19.73 ab		Rio Colorado	2.83	55.00 ab
	Atlantic	3.08	17.08 bc		Atlantic	2.67	49.33 abc
	Mountain Rose	2.91	16.25 bcd		DT6063-1R	2.58	48.42 abc
Medium	Rio Colorado	2.64	13.55 cde	Medium	Mountain Rose	2.33	43.92 bcd
	Canela Russet	2.50	12.79 def		Purple Majesty	2.33	42.83 bcd
	DT6063-1R	2.25	11.83 ef		Russet Burbank	2.17	41.08 bcd
	Rio Grande Russet	2.36	11.82 ef		Canela Russet	1.83	35.00 bcde
Low	Ranger Russet	2.00	9.59 ef	Low	Ranger Russet	1.33	27.17 cde
	Freedom Russet	2.08	9.25 f		Rio Grande Russet	1.17	21.50 de
	Russet Burbank	1.25	4.29 g		Freedom Russet	1.00	21.08 de
	CO94035-15RU	1.16	4.25 g		CO94035-15RU	0.57	13.97 e
P=0.05			3.82	*P*=0.05			26.67

For mean rank estimate, means followed by the same letter are not significantly different at $p=0.05$.

Table 3 Potato cultivars with corresponding tuber severity index - % incidence x severity rating (1–5) (average of three years of SLV field results and average of both greenhouse crops – trial 4)

Greenhouse (2 crops)				Field (3years)			
Severity Level	Potato Cultivar	Mean Severity Index	Mean Rank Estimate	Severity Level	Potato Cultivar	Mean Severity Index	Mean Rank Estimate
High	Mountain Rose	283.98	22.08 a	High	Rio Colorado	257.19	110.21 a
	Rio Colorado[a]	308.57	21.41 a		Mountain Rose	198.88	106.18 ab
	Superior	250.00	21.17 a		DT6063-1R	188.38	98.78 abc
	DT6063-1R	275.00	20.88 a		Superior	117.50	94.34 abc
Medium	VC0967-2R/Y	220.83	20.00 ab	Medium	VC0967-2R/Y	112.94	88.62 bcd
	VC1002-3W/Y	200.00	18.83 abc		Purple Majesty	79.44	86.12 bcd
	Purple Majesty	156.94	17.46 bc		VC1002-3W/Y	54.17	78.29 cd
	Atlantic	133.33	15.67 c		Atlantic	42.11	68.34 d
Low	Ranger Russet	12.87	8.41 d	Low	Ranger Russet	5.50	40.29 e
	Freedom Russet	15.98	8.00 d		Freedom Russet	2.50	33.93 e
	Canela Russet	1.39	6.58 d		Rio Grande Russet[b]	0.00	27.76 e
	CO94035-15RU	0.00	6.18 d		CO94035-15RU	0.38	27.62 e
	Russet Burbank	0.00	6.17 d		Canela Russet	0.00	24.38 e
	Rio Grande Russet	0.00	6.17 d		Russet Burbank	0.00	24.38 e
P=0.05			3.34	*P*=0.05			20.86

[a] Rio Colorado had the highest Mean Severity Index, yet was ranked 2nd. This was due to variability among reps for this cultivar.

[b] Rio Grande Russet (27.76) resulted in a higher ranking than CO94035-15RU (27.62) even though Rio Grande Russet has a lower Mean Severity Index reading, because some reps were missing in the field trials for Rio Grande Russet.

For Mean Rank Estimate, means followed by the same letter are not significantly different at $p=0.05$.

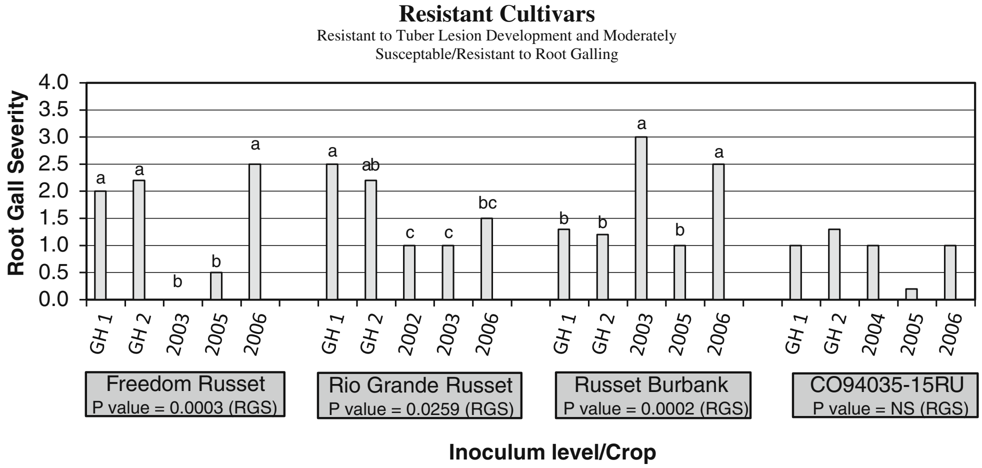


Fig. 8 Evaluation of four potato cultivars which are resistant to powdery scab tuber lesion development, comparison of three years of field data to two greenhouse crops evaluating powdery scab root gall severity. x-axis: GH 1 & 2 = greenhouse crops #1 & 2; 2002, 2003, 2004, 2005, 2006 = yrs of field data. Data was analyzed within each cultivar to determine differences between greenhouse and field results. Bars with the same letters are not significant at P=0.05 for each cultivar

were grouped by susceptibility level (high, medium, low) based on the statistical grouping of the mean rank estimate. For example, Freedom Russet was among the lowest ranking for root gall severity in the field over three years (1.00). To compensate for the higher greenhouse results (2.08), the scale was adjusted from 0 to 1.75 for the field and 0 to 2.20 for the greenhouse. This adjustment still keeps Freedom Russet in the low root gall severity category while acknowledging the higher root gall severity obtained in the greenhouse. When examining the fourteen cultivars for root gall severity and tuber severity index, the relative rankings in general remained similar between the field and greenhouse. At most, a cultivar only differed by one grouping category.

The goal of conducting cultivar evaluation trials is to discover potato germplasm that is resistant to powdery scab root and tuber development. Based on this relative ranking system, cultivars which had relatively low disease expression in the field were also low in the greenhouse for root gall severity and tuber severity index.

In conclusion, it was observed that the variables of soil type, inoculum level, inoculum source, temperature, and soil moisture played an important role in the greenhouse for determining powdery scab symptom expression in four potato cultivars. The combination of these variables which produced symptoms that most closely matched SLV field data, provided the most consistent disease expression, and produced the highest disease levels were: a soil type with 50% sand, an inoculum level of 1 sb/g of soil (mixed uniformly throughout the soil), and a high soil moisture (an average between 5 to 10 cbars) during and after tuber set. These variables, in addition to keeping the soil temperature at a range of 11–18°C from tuber initiation through bulking, were found to produce greenhouse results that best matched SLV field data in a greenhouse for the four cultivars evaluated.

The resulting greenhouse assay was used to evaluate 14 potato cultivars for powdery scab disease expression. Disease data from the greenhouse was compared with three years of SLV field data in order to determine the accuracy of disease expression in the greenhouse. The greenhouse assay produced powdery scab results which were more consistent than field results and tended to match the year of field data with the highest levels of disease. Means were calculated for the greenhouse crops and years of field data and were correlated by developing a relative ranking table in order to compare both greenhouse and field results. This allowed for a realistic comparison between the greenhouse and the field. The greenhouse assay developed in this project was determined to be a good alternative to using field trials to evaluate cultivars for susceptibility to powdery scab. Also, the cultivars CO94035-15RU, Freedom Russet, Ranger Russet, and possibly Rio Grande Russet and Russet Burbank, could be used as germplasm material for powdery scab resistance breeding programs based on the data collected in this project.

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References

Baldwin, S.J., R.A. Genet, R.C. Butler, and J.M.E. Jacobs. 2008. A greenhouse assay for powdery scab (*Spongospora subterranea* f.sp. *subterranea*) resistance in potato. *Potato Research* 51: 163–173.

Braithwaite, M., R.E. Falloon, R.A. Genet, A.R. Wallace, J.D. Fletcher, and W.F. Braam. 1994. Control of powdery scab of potatoes with chemical seed tuber treatments. *New Zealand Journal of Crop and Horticultural Science* 22: 121–128.

Christ, B.J. 2005. Integrated management of powdery scab. *Proceedings of Wisconsin's Annual Potato Meeting*. University of Wisconsin-Madison Extension, Wisconsin Agricultural Experiment Station.

de Boer, R. 1991. Evaluation of potato cultivars in the greenhouse and field for resistance to powdery scab. *Australian Journal of Experimental Agriculture* 31: 699–703.

Douches, D.S. 2005. Breeding and genetics for the improvement of potato (*Solanum tuberosum L.*) for yield, quality, and pest resistance. http://www.msu.edu/user/douchesd/overview/overview.html. Accessed 28 September 2005.

Falloon, R.E., R.A. Genet, A.R. Wallace, and R.C. Butler. 2003. Susceptibility of potato (*Solanum tuberosum*) cultivars to powdery scab (caused by *Spongospora subterranea f. sp. subterranea*), and relationships between tuber and root infection. *Australasian Plant Pathology* 32: 377–385.

Harrison, J.G., R.J. Searle, and N.A. Williams. 1997. Powdery scab disease of potato - a review. *Plant Pathology* 46: 1–25.

Holm, D.G. 2005. The search for new potato cultivars. http://www.SLVRC.colostate.edu/searchforpotcult.html. Accessed 28 September 2005.

Jellis, G.J., P.S. Phul, and N.C. Starling. 1987. Evaluation of potato germplasm for resistance to powdery scab (*Spongospora subterranea*). *Annals of Applied Biology* 110 (Supplement). *Tests of Agrochemicals and Cultivars* 8: 154–155.

Lees, A.K., P. van de Graaf, and S. Wale. 2008. The identification and detection of *Spongospora subterranea* and factors affecting infection and disease. *American Journal of Potato Research* 85: 247–252.

Merz, U. 2000. Powdery scab research in Switzerland. In: *Proceedings First European Powdery Scab Workshop, SAC, Aberdeen, Scotland, July 20–22, 2000*, eds. Mertz U, Lees AK.

Merz, U., and R.E. Falloon. 2009. Review: powdery scab of potato – increased knowledge of pathogen biology and disease epidemiology for effective disease management. *Potato Research* 52: 17–37.

Merz, U., V. Martinez, and R. Schwarzel. 2004. The potential for the rapid screening of potato cultivars (*Solanum tuberosum*) for resistance to powdery scab (*Spongospora subterranea*) using a laboratory bioassay. *European Journal of Plant Pathology* 110: 71–77.

Miller, J. 2001. Powdery scab workshop - summary notes. Alamosa, CO January 11, 2001. http://www.uidaho.edu/ag/plantdisease/scabnote.htm. Accessed 9 June 2005.

Taylor, P.A., S.P. Flett, R.F. de Boer, and D. Marshall. 1986. Effects of irrigation regimes on powdery scab disease and yield of potatoes. *Australian Journal of Experimental Agriculture* 26: 745–750.

van de Graaf, P., A.K. Lees, and J.M. Duncan. 2000. Epidemiology and control of *Spongospora subterranea* f. sp. *subterranea*, with special reference to zoospore release and bait plant infection. In: *Proceedings First European Powdery Scab Workshop, SAC, Aberdeen, Scotland, July 20–22, 2000*, eds. Mertz U, Lees AK.

van de Graaf, P., A.K. Lees, and J.M. Duncan. 2002. Effect of inoculum level and environmental conditions on powdery scab and root galling in potato. *Proceedings Crop Protection in Northern Britian 2002.* Dundee, UK: Scottish Crop Research Institute. pp 281–286.

van de Graaf, P., A.K. Lees, S.J. Wale, and J.M. Duncan. 2005. Effect of soil inoculum level and environmental factors on potato powdery scab caused by *Spongospora subterranea*. *Plant Pathology* 54: 22–28.

Wale, S. 2001. The a to z of powdery scab and its control. *Presentation given at the Potato Disease Workshop on Powdery Scab, coordinators R Zink and R Davidson, Alamosa CO, 11 January 2001.*

Zink, R.T., R.D. Davidson, and A. Houser. 2004. Control strategies for powdery scab of potato. *American Journal of Potato Research: Abstracts* 81: 95–96.