Screening *Capsicum annuum* Accessions for Resistance to Six Isolates of *Phytophthora capsici*

Byron L. Candole and Patrick J. Conner¹

University of Georgia–Tifton Campus, Horticulture Department, 4604 Research Way, Tifton, GA 31793

Pingsheng Ji

University of Georgia, College of Agricultural and Environmental Sciences, Coastal Plain Experiment Station, Plant Pathology Department, P.O. Box 748, Tifton, GA 31793

Additional index words. pepper, *Phytophthora* blight, root rot, stem blight, foliar blight, host resistance

Abstract. *Phytophthora* blight caused by *Phytophthora capsici* Leon. is one of the most important diseases of bell peppers (*Capsicum annuum* L.) in Georgia. The level of resistance in commercial bell pepper cultivars is not effective in managing this disease in moist and humid conditions, and new sources of resistance are needed. A mixture of six Georgia isolates of *P. capsici* was used for greenhouse mass screening of 2301 accessions of *Capsicum annuum*. From the initial screening, 77 accessions were identified as resistant to *P. capsici*-induced root rot. From those 77 accessions, 28 accessions were selected for seed increase and further replicated root inoculation tests. Replicated tests confirmed the resistance of 14 of the 28 accessions, although genetic variability within the accessions hampered the analysis of resistance in some accessions. Two accessions, PI 201237 and PI 640532, demonstrated consistently high levels of resistance to root rot. These two accessions are potential sources of resistance genes that can be incorporated into commercial bell pepper cultivars.

Bell pepper (*Capsicum annuum*) is one of the economically important crops in the state of Georgia where the total farm-gate value of bell pepper was ≈\$100 million in 2007 (Boatright and McKissick, 2008). *Phytophthora* blight, caused by the oomycete pathogen *Phytophthora capsici* (Leonian, 1922), is a serious threat to production of peppers worldwide (Babadoost, 2004). This disease has become a major disease constraint to bell pepper production, affecting the plants at all growth stages (from seedling to adult plant) and all plant parts, including roots, leaves, stems, and fruits. *P. capsici* attacks the roots at all developmental stages, causing sudden wilt and collapse of the infected plant (Lefebvre and Palloix, 1996). *Phytophthora* infection is enhanced by warm temperatures and frequent rainfall (Weber, 1932), conditions that are common in the southeastern United States during the summer months. In Georgia, the most common symptoms caused by *P. capsici* infection are root rot, crown rot, and leaf blight.

Recommended management strategies for *P. capsici* include cultural practices that ensure well-drained soils in the field, crop rotation, soil solarization, use of mulches to prevent splash/soil dispersal, and chemical control

(Ristaino and Johnston, 1999). The host range of *P. capsici* includes multiple crops and weed species (Erwin and Rebeiro, 1996; French-Monar et al., 2006). Oospores can persist in the soil for long periods (Hausbeck and Lamour, 2004). For these reasons, crop rotation with other major crops is often not an effective management option. The fungicide mefenoxam has been heavily relied on to control *P. capsici*. However, because this chemical has a single mode of action, resistance has developed in *P. capsici* and many field isolates are now unresponsive to mefenoxam application (Café-Filho and Ristaino, 2008; French-Monar et al., 2005; Hausbeck and Lamour, 2004).

The use of *P. capsici*-resistant bell pepper cultivars is an important aspect in the management of this disease. *P. capsici*-resistant bell pepper cultivars such as Paladin, Aristotle, Revolution, and Alliance are available commercially, but their resistance is not consistently effective against *Phytophthora* blight in all locations or production systems (Oelke et al., 2003). Additionally, most resistant cultivars lack the horticultural characteristics necessary to compete with susceptible cultivars (Ristaino and Johnston, 1999). ‘Aristotle’ is the most widely grown bell pepper cultivar in southern Georgia where its level of resistance is often not effective against root rot, foliar, and stem blights under warm temperatures and high moisture conditions.

The development of new resistant pepper cultivars is dependent on the identification of

resistance in the pepper germplasm. Several partial screenings have been made for resistance to *P. capsici* in the *Capsicum* germplasm. Kimble and Grogan (1960) examined 613 pepper lines and cultivars and found three (PI 188476, PI 201232, PI 201234) with high levels of resistance to *Phytophthora* root rot. Barksdale (1984) examined 24 PI lines and several cultivars for foliar resistance. PI 201232 and PI 201234, which were previously shown to be resistant to crown and root rot, were shown to also exhibit high levels of foliar resistance. Reifschneider et al. (1986) examined seven genotypes derived from resistant cultivars or breeding lines and found one line, CNPH 286, to be reliably resistant to root rot. PI 201232 and PI 201234 or lines obtained from them have been the main sources of resistance used in early breeding work in the United States and Europe (Ortega et al., 1991). Two lines from Mexico, Line 29 and Criollo de Morelos-334 (CM-334), were also found to exhibit high levels of resistance (Ortega et al., 1991). Most recent work has focused on resistance from the landrace CM-334, which has demonstrated the highest level of resistance to *P. capsici* to date when screened for root rot resistance and leaf resistance (Ortega et al., 1991; Walker and Bosland, 1999). CM-334 is resistant to *Phytophthora capsici* in roots, stems, and leaves (Alcantara and Bosland, 1994; Bosland and Lindsey, 1991; Walker and Bosland, 1999). However, Walker and Bosland (1999) found that in progenies derived from CM-334, foliar blight resistance and root rot resistance were controlled by independently segregating genes. Further work by Sy et al. (2005) demonstrated that stem blight resistance from CM-334 was controlled by a single gene, *Psrr*, when ‘Early Jalapeno’ was the susceptible parent and that this gene was inherited independently from those controlling foliar blight and root rot resistance. Thus, it appears that foliar blight, stem blight, and root rot are separate disease syndromes that need to be analyzed independently.

Reliance on a small number of resistance sources may lead to undesirable levels of genetic vulnerability. No systematic searches have been conducted in recent years using the pepper germplasm available at the USDA National Plant Germplasm System (R. Jarrett, personal communication). The objective of this study was to conduct a more thorough screening of this germplasm to find sources of resistance to *P. capsici* that could be incorporated into a new commercial bell pepper cultivar for the Georgia production region.

Materials and Methods

Test plants. *Capsicum annuum* accessions were obtained from the USDA, ARS Plant Genetic Resources Conservation Unit in Griffin, GA. The total of 3118 accessions used in this study represented all the *C. annuum* accessions available from this location. The term accession is used in this article to refer to the original seed lot that was

Received for publication 26 Oct. 2009. Accepted for publication 16 Dec. 2009.

¹To whom reprint request should be addressed; e-mail pconner@uga.edu.

obtained from the USDA under a particular accession number. Because some accessions represent landraces or were derived from mixed fruit collections, accessions are not necessarily genetically homogenous. The term "line" is used to refer to the selfed seed collected from individual plants grown out from accession seed. Multiple lines from the same accession may or may not be genetically homogenous, depending on the genetic variation present in the original accession. The test plants were watered twice daily and fertilized twice a week with water-soluble fertilizer (24N-6P-16K) diluted to provide 315 ppm nitrogen. All tests were performed in the greenhouse where the air temperature before and during the disease incubation process had a diurnal range of 13 to 30 °C. 'Camelot' and Criollo de Morelos 334 (CM-334) were used as the susceptible and resistant controls, respectively, in all tests. CM-334 was kindly provided by P. Bosland (New Mexico State University) and 'Camelot' was obtained from Rupp Seeds (Wauseon, OH).

P. capsici isolates and inoculum preparation. Three virulent isolates from the A1 (PC-F6S1, PC-F6S3, PC-1A1) and three from the A2 (PC-F1R3, PC-F1R6, PC-F1S12) mating types of *P. capsici* were used in the mass screening and subsequent inoculation tests. These isolates were all obtained from grower fields in Tift County, GA. Isolate PC-1A1 was isolated from summer squash (*Cucurbita pepo* L.), and then inoculated to and reisolated from bell pepper before use. All other isolates were obtained directly from bell pepper before use. A mixture of zoospores from these six isolates was used in inoculating the test plants. The zoospores were produced aseptically by transferring 10 agar plugs from the advancing portion of 5-d-old cultures (25 °C, under dark condition) of *P. capsici* in 5% (v/v) clarified V8 juice agar (Kuhajek et al., 2003) to 100 × 15-mm petri dishes (≈12 plates/isolate) and 10 mL of clarified V8 juice was added thereafter. After 24 h of incubation at 25 °C under dark conditions, the V8 juice in each plate was replaced with 10 mL sterile mineral salt solution (MSS) (Kuhajek et al., 2003) and the plates were incubated at 20 °C 30 cm under two fluorescent lights (cool white, 20 W, 25 °C, 35 μmol·m⁻²·s⁻¹) for 24 h. The MSS from each plate was then replaced with the same volume of fresh MSS and the plates were allowed to incubate for 3 more days.

Zoospores from each isolate were harvested separately. To harvest the zoospores, the MSS was removed from each plate and then washed twice with 10 mL of sterile distilled water. After the second washing, 10 mL of sterile distilled water was added to each plate and placed in the refrigerator (1.3 °C) for 45 min. The plates were then incubated at room temperature and monitored for zoospore release. The zoospore suspension from each petri dish was then transferred very slowly to a 250-mL graduated cylinder and left undisturbed for 5 min. The upper 50 mL of the zoospore suspension was pipetted out and transferred to a 50-mL conical centrifuge

tube. The tube was then inverted gently two to three times to evenly distribute the zoospores in the suspension. One milliliter of the suspension was transferred to a 2-mL microcentrifuge tube with flat cap and vortexed for 90 s to encyst the zoospores. The zoospore concentration was determined using a hemacytometer and adjusted to 2000 zoospores/mL (Bosland and Lindsey, 1991). Equal volumes of zoospore suspensions were then combined for inoculation.

Primary screening of accessions for root rot resistance. A total of six to 12 plants was tested for each accession. Seeds from each accession were sown in plastic cells of a multipot bedding plant container (Com-Pack D806; Hummert International, St. Louis, MO). Each cell measured 6 cm × 4 cm × 5.5 cm and contained Redi Earth plug and seedling mix (Sun Gro, Bellevue, WA). The cells containing the seeds were then placed in 52.3 cm × 25.9 cm × 6.1-cm plastic trays with drainage holes (F1020 flats; Hummert International).

Root inoculation was made according to a previously described procedure (Bosland and Lindsey, 1991). Briefly, 2 h before inoculation, the trays containing 14-d-old pepper seedlings were placed in water-filled trays to saturate the soil around the roots. A 5-mL zoospore suspension was then delivered onto each cell using an automatic dispenser (Finpipette, Vantaa, Finland) resulting in a final concentration of 10,000 zoospores per cell. The saturated condition was maintained for another 48 h and disease evaluation was performed 14 d after inoculation. The plants were evaluated based on a 10-point scale (Bosland and Lindsey, 1991): 0 = no response, vigorous, healthy; 3 = brown roots, slight stunting, very small lesions on stems; 5 = brown roots, small lesions on stems, lower leaves wilted, stunted plants; 7 = brown roots, large lesions on stems, girdling, whole plant wilted, and stunted; 9 = death. Even numbers corresponded to intermediate response. A disease index value of 2 or less was considered resistant, and a value greater than 2 was susceptible. Seeds from individual plants from each accession that were identified as resistant and survived to fruit set were harvested separately. To produce seed, plants were kept in a screened greenhouse with an absence of pollinators. Seed was collected from ripe fruit, hand-separated, dried on a laboratory benchtop, and kept refrigerated until used.

Retest of primary selections. A total of 28 accessions in which three or more inoculated plants survived the primary screen to seed set were chosen for seed increase and replicated inoculation tests to confirm the results of the mass screening. Individual surviving plants from each of the 28 accessions were selfed to produce 109 seed lines for testing. The seeds from each surviving plant of each accession were sown separately in plastic cells of a multipot bedding plant container (Com-Pack D812; Hummert International) containing the same growing medium as described previously.

Each cell measured 4 cm × 3 cm × 5.5 cm. A total of six seeds was planted for each test line within an accession at the rate of one seed per cell. The cells containing the seeds were then placed in plastic trays as described earlier. This particular test was performed in a randomized complete block design with four replications of six seedlings per test line. Root inoculation and root rot ratings were performed as described previously.

Field test. The resistance of 12 accessions that were rated resistant in the primary screen and had produced sufficient seed were evaluated under field conditions in the fall of 2008. Seeds from at least two lines within an accession were mixed in cases in which there was not enough seed from a single line to complete the test. 'CCM-334' and 'Camelot' were used as the resistant and susceptible controls, respectively. The field test was conducted at the Black Shank Farm of the University of Georgia's Coastal Plain Experiment Station, Tifton, GA. The soil type was fuquay loamy sand (88% sand, 8% silt, 4% clay; pH 5.5 to 6.0; 2% organic matter; loamy, siliceous thermic Arenic Plinthic Paleudults). The field plots used in the study were naturally infested with *P. capsici*. Raised soil beds were formed by using a commercial tractor-drawn bedder (Kennco's Blue Bedder Model BL4000BK; Kennco, Mfg., Ruskin, FL). Drip irrigation tapes (Aqua-Traxx Premium drip tape; Toro Ag Irrigation Business, El Cajon, CA) were installed at a depth of 2.5 cm in the center of the beds and a white low-density polyethylene (LDPE) plastic mulch (0.5-mil thickness) covered the beds. Each bed for a single replicate measured 4.6 m long, 0.8 m wide, and 0.3 m high. The pepper accessions or cultivars were arranged in a randomized complete block design with five replications and each replicate consisted of a total of 32 plants for each accession. Seven-week-old transplants were established on double rows with the distance between rows and between plants within a row at 30 cm. All treatments were fertigated once a week (130 kg·ha⁻¹ of nitrogen, 48 kg·ha⁻¹ of P₂O₅, 27 kg·ha⁻¹ K₂O) by injecting the liquid fertilizer into the drip irrigation system. Drip irrigation was applied and insects and weeds were controlled according to the practices recommended by the University of Georgia Cooperative Extension Services (Kelley et al., 2009).

At maturity, all treatments were evaluated for root rot severity by digging plants, washing the roots, and assessing the percentage of root rot or percentage of the root system with root discoloration or browning and for plant survival, which is the percentage of plants that survived the disease. The presence of brown roots was taken as an indication of phytophthora root rot because this is a common symptom (Hausbeck and Lamour, 2004) and the disease was prevalent in this location. Mean separations for variables percent root discoloration and percent survival were performed by means of Duncan's multiple range test (DMRT) after a significant F-test resulting from the analysis of variance procedure.

Results

Only 2301 (74%) of the 3118 accessions germinated to yield at least three plants for root inoculation. As a result of the large number of accessions tested, accessions that germinated poorly were not retested. Mean root rot ratings of accessions ranged from 1 to 9 with the majority of accessions rated as very susceptible (Fig. 1). Results of the original screening have been placed on the U.S. Dept. Agr. Germplasm Resources Information Network web site (<http://www.ars-grin.gov/cgi-bin/npgs/html/desc.pl?116072>). Of the 2301 tested accessions, 77 (3.3%) had a mean root rot severity of 2 or less and were considered resistant. Thirty-seven of those 77 (48%) accessions had at least one plant that survived to fruit set (Table 1). Plants did not survive to fruit set primarily as a result of latent infections with *P. capsici*, transplant shock resulting from repotting after scoring roots, poor adaptation to greenhouse culture, and the long times needed for some genotypes to produce seed. Unfortunately, some accessions were also very poor producers of seed, at least under these growing conditions, and did not provide enough seed for further replication and/or field testing. As a result of the large number of lines sampled in this project, no attempt was made to further test accessions that did not survive to fruit maturity. However, these accessions are available on the web site listed previously and should be considered in future studies looking for potential new sources of resistance to *P. capsici*.

Five accessions (PI 201231, PI 201239, PI 593485, PI 593493, PI 593573) were consistently resistant (root rot severity rating = 1) with a sd of zero and plant survival ranging from 30% to 100% (Table 1). A further 20 accessions responded with all plants scored within the resistant range of 1 to 2 root rot severity rating. Fifteen of these 20 accessions had a most commonly observed rating of 1 and five had a most commonly observed rating of 2. Although the other 12 accessions were resistant based on their mean root rot severity rating, and most plants within an accession were within the resistant range (0 to 2), individual plant responses within the accession ranged from resistant (1) to susceptible (3 to 6). The resistant control CM-334 had an average rating of 1 with 100% survival and the susceptible control, 'Camelot', had an average rating of 9 with no surviving plants (Table 1).

Of the 37 accessions that survived to seed set, 28 accessions produced enough seed for further replicated testing. Selfed seed from each surviving plant of the original accession was tested separately so that most accessions were represented by multiple seed lines. Based on the average root rot severity over all lines tested per accession, results from the replicated inoculation tests (with greater sample sizes) showed that of the 28 accessions tested, 14 confirmed their resistant reactions from the previous mass screening tests (root rot severity rating 2.0 or less) and

Fig. 1. Frequency distribution of mean root rot severity derived from a mass screening of *Capsicum annuum* accessions with *Phytophthora capsici*. Only the 2301 accessions with three or more scored plants are included in the distribution.

Table 1. Accessions of *Capsicum annuum* that were identified as resistant and survived to seed set from mass screening against six Georgia isolates of *Phytophthora capsici*.

Accession	Name	Country of origin	Root rot severity			Survival ^y (%)
			Range	Mean ^z	sd	
PI 201231	Chilhaucle Amarillo	Mexico	1	1.0	0.0	100
PI 201239	Chile Ancho San Luis	Mexico	1	1.0	0.0	100
PI 593485	10210	Mexico	1	1.0	0.0	30
PI 593493	10258	Mexico	1	1.0	0.0	33
PI 593573	10688	Brazil	1	1.0	0.0	33
PI 439273		Mexico	1-2	1.1	0.1	57
PI 593495	10263	Mexico	1-2	1.1	0.1	33
PI 183922	Mirch	India	1-2	1.2	0.2	33
PI 511882	Chile negro	Mexico	1-2	1.2	0.2	60
PI 593572	10687	Brazil	1-2	1.2	0.1	60
PI 631147	Perennial		1-3	1.2	0.2	33
PI 640833	Cascabella	United States	1-2	1.2	0.2	50
PI 201237	Chilpotle Mico	Mexico	1-3	1.3	0.3	83
PI 439302		Mexico	1-2	1.3	0.2	17
PI 511884	Chile de Chapa	Mexico	1-2	1.3	0.2	33
PI 566811	Chile criollo	Mexico	1-2	1.3	0.2	100
PI 593564	10641	Mexico	1-2	1.3	0.2	40
PI 640448	Szechwan 3	Taiwan	1-2	1.4	0.2	33
PI 640532	871076	Mexico	1-2	1.4	0.2	33
PI 511883	Chile criollo	Mexico	1-3	1.5	0.3	50
PI 640461	83-168	China	1-2	1.5	0.2	73
PI 640641	IR	Indonesia	1-6	1.5	0.5	40
PI 640659	Mun	Thailand	1-2	1.5	0.2	13
Grif 9109	BG-912	Mexico	1-2	1.6	0.2	100
PI 640663	PBC 602	Taiwan	1-2	1.6	0.2	11
PI 640670	Singh 4	India	1-2	1.6	0.2	9
PI 224438	No. 1713	Mexico	1-2	1.7	0.2	100
PI 593511	10325	Mexico	1-3	1.7	0.3	33
PI 640480	HDA 336	France	1-6	1.7	0.7	43
PI 640560	Phyo 636	Netherlands	1-4	1.7	0.5	43
PI 640588	YCb 76105	United States	1-3	1.7	0.3	33
PI 640671	CA 8	Sri Lanka	1-2	1.7	0.2	17
PI 640581	U-Kimba	Nigeria	1-4	1.8	0.3	27
PI 640516	Chicken Heart	Taiwan	1-4	1.9	0.3	25
PI 640582	UL-2190	Nigeria	1-3	2.0	0.3	30
PI 640682	PBC 661	Tanzania	1-6	2.0	0.5	11
PI 640803	Red Hot	Philippines	1-2	2.0	0.4	10
	Criollo de Morelos 334 (resistant control)	Mexico	0-1	1.0	0.0	100
	Camelot (susceptible control)	United States	9	9.0	0.0	0

^zBased on a 0 to 9 scale (Bosland and Lindsey, 1991): 0 = no response; 3 = brown roots, slight stunting, very small lesions on stems; 7 = brown roots, large lesions on stems, girdling, whole plant wilted, and stunted; 9 = dead plants. A resistant (R) reaction is a severity rating of less or equal to 2 and a susceptible (S) reaction is a severity rating of greater than 2.

^ySurvival (%) = (number of plants surviving to fruit set/total number of plants tested per accession) × 100.

the other 14 accessions had susceptible reactions (root rot severity rating greater than 2.0) (Table 2). However, there was moderate variation among lines within an accession as well as among plants within a line. For example, accession PI 201231 had an overall score of 2.5 but had three lines with an average score in the resistant range (1.3, 1.8, 2.0) and two lines in the susceptible range (2.4, 5.3). Only in accessions PI 201237 and PI 640532 did all plants from all lines responded within the resistant range.

Under field conditions, root discoloration ranged from 11.5% (PI 593573) to 30.4% (PI 640527), whereas the plant survival at maturity ranged from 95.3% (PI 511883) to 100% (PI 566811, PI 593573, PI 640516) (Table 3). The low level of root discoloration in PI 640560, PI 640532, PI 640581, and PI 593573 was comparable with the low level of root discoloration in the resistant control, CM-334. Only PI 511883 had a plant survival (95.3%) that was significantly lower than the plant survival of CM-334 aside from the susceptible control, 'Camelot'.

Discussion

To our knowledge, this is the first reported wide-scale testing of *Capsicum* germplasm for resistance to *P. capsici* since the original work of Kimble and Grogan (1960), although doubtless much screening work has been done in breeding programs throughout the world. These tests demonstrated the availability of accessions that are potential sources of resistance to Georgia isolates of *P. capsici* and potentially can be incorporated into commercial bell pepper cultivars.

The majority of the 28 accessions included in the replicated root inoculation tests came from Mexico (15 accessions), whereas two accessions each came from Brazil, Taiwan, Nigeria, and United States and one accession each from China, France, The Netherlands, and Indonesia with one accession (PI 631147) of unknown origin (Table 1). These accessions express a wide range of fruit and plant morphological characteristics, including many that had small very pungent fruits.

However, some accessions, including PI 640480 and PI 640532, had relatively large pod size and good levels of resistance. None of these accessions were previously identified or reported as resistant except PI 640560 (cv. PHYO 636), an accession that was previously reported resistant to root rot (Palloix et al., 1988), was resistant in the mass screening test (Table 1) but was observed to be susceptible in the subsequent replicated inoculation test (Table 2). Of the three accessions reported as resistant by Kimble and Grogan (1960), two (PI 188476 and PI 201234) were found to be susceptible in this screening and one (PI 201232) was resistant but only a single plant germinated for testing. Differences in susceptibility ratings between the previous and current studies may be the result of differences in the isolates used for testing or in the inoculation methods used.

Table 2. The reaction of selected *Capsicum annuum* accessions in replicated inoculation tests against a mixture of six Georgia isolates of *Phytophthora capsici*.

Accession	Name/Variety	Line number ^a	Mean ^b	Root rot severity		
				Range	Mode	sd
Grif 9109	BG-912	1	1.3	0-3	2	0.9
Grif 9109	BG-912	2	1.9	1-3	2	0.6
Grif 9109	BG-912	3	1.8	0-4	3	1.3
Grif 9109	BG-912	4	2.0	1-9	1	1.7
Grif 9109	BG-912	5	2.2	0-5	2	1.7
			(1.8)			(1.3)
PI 201231	Chilhaucle Amarillo	1	2.4	1-3	3	0.7
PI 201231	Chilhaucle Amarillo	2	1.3	1-2	1	0.4
PI 201231	Chilhaucle Amarillo	3	1.8	1-3	2	0.5
PI 201231	Chilhaucle Amarillo	4	2.0	1-5	2	1.0
PI 201231	Chilhaucle Amarillo	5	5.3	3-9	9	1.6
			(2.5)			(1.7)
PI 201237	Chilpotle Mico	1	1.3	0-2	2	0.8
PI 201237	Chilpotle Mico	2	1.7	1-2	2	0.4
PI 201237	Chilpotle Mico	3	1.4	1-2	1	0.4
PI 201237	Chilpotle Mico	4	1.0	0-2	1	0.7
PI 201237	Chilpotle Mico	5	1.3	1-2	2	0.4
			(1.3)			(0.6)
PI 201239	Chile Ancho San Luis	1	2.3	1-3	2	0.4
PI 201239	Chile Ancho San Luis	2	1.3	0-3	2	0.9
PI 201239	Chile Ancho San Luis	3	1.5	1-2	1	0.4
PI 201239	Chile Ancho San Luis	4	1.2	0-4	1	0.8
PI 201239	Chile Ancho San Luis	5	1.0	1	1	0.0
PI 201239	Chile Ancho San Luis	6	2.0	1-5	2	0.1
			(1.5)			(0.7)
PI 224438	No. 1713	1	1.4	1-2	1	0.5
PI 224438	No. 1713	2	1.5	0-3	2	0.4
PI 224438	No. 1713	4	1.1	0-2	1	0.1
PI 224438	No. 1713	5	1.4	1-2	1	0.2
PI 224438	No. 1713	6	1.3	1-2	1	0.4
			(1.3)			(0.4)
PI 439273		1	1.3	0-3	2	0.9
PI 439273		2	1.8	1-3	1	0.4
PI 439273		3	3.0	1-8	3	1.1
PI 439273		4	1.9	1-3	2	0.5
			(2.0)			(1.0)
PI 511882	Chile negro	1	2.9	1-4	4	1.0
PI 511882	Chile negro	2	7.5	2-9	9	1.8
PI 511882	Chile negro	3	4.5	1-9	2	2.2
			(5.0)			(2.5)
PI 511883	Chile criollo	1	0.7	1-5	3	1.6
PI 511883	Chile criollo	2	2.0	2	2	0.0
PI 511883	Chile criollo	3	2.3	0-5	2	1.6
			(2.4)			(1.3)
PI 566811	Chile criollo	1	1.3	1-3	1	0.4
PI 566811	Chile criollo	2	1.4	0-2	2	0.6
PI 566811	Chile criollo	3	1.4	1-2	1	0.5
PI 566811	Chile criollo	4	1.1	0-2	1	0.7
PI 566811	Chile criollo	5	1.4	1-2	1	0.5
PI 566811	Chile criollo	6	1.9	1-3	2	0.5
PI 566811	Chile criollo	7	1.3	0-3	2	0.9
PI 566811	Chile criollo	8	1.2	0-2	2	0.8
PI 566811	Chile criollo	9	1.5	1-2	1	0.5
			(1.4)			(0.6)
PI 593485	10210	2	1.3	0-9	1	0.9
PI 593493	10258	1	1.3	0-7	1	1.1
PI 593493	10258	2	1.0	0-2	1	0.7
PI 593493	10258	3	0.8	0-1	1	0.4
			(1.0)			(0.8)
PI 593495	10263	1	2.6	0-9	2	1.9
PI 593495	10263	3	2.0	0-5	1	1.7
			(2.3)			(1.7)
PI 593511	10325	1	3.6	2-9	3	1.6
PI 593511	10325	2	2.2	1-9	2	0.9
PI 593511	10325	3	2.5	2-9	2	0.7
			(2.8)			(1.2)
PI 593564	10641	1	2.0	1-9	2	0.9
PI 593564	10641	2	2.0	0-4	3	0.5
PI 593564	10641	3	1.6	1-3	1	0.6
PI 593564	10641	4	1.5	0-3	1	0.7
			(1.8)			(0.7)

(Continued on next page)

Table 2. (Continued) The reaction of selected *Capsicum annuum* accessions in replicated inoculation tests against a mixture of six Georgia isolates of *Phytophthora capsici*.

Accession	Name/Variety	Line number ^a	Root rot severity			
			Mean ^b	Range	Mode	SD
PI 593572	10687	1	2.8	2–4	4	1.1
PI 593572	10687	2	0.5	0–1	1	0.5
PI 593572	10687	3	1.2	0–2	2	0.8
PI 593572	10687	4	1.6	1–3	2	0.6
PI 593572	10687	5	1.3	0–2	2	0.6
PI 593572	10687	6	1.3	1–2	1	0.8
			(1.4)			(1.0)
PI 593573	10688	1	1.1	1–3	1	0.1
PI 593573	10688	2	1.4	0–2	2	0.6
PI 593573	10688	3	1.3	1–2	1	0.4
			(1.3)			(0.4)
PI 631147	Perennial	1	2.9	1–9	3	1.5
PI 631147	Perennial	2	1.9	0–9	1	1.4
PI 631147	Perennial	3	2.3	0–4	2	0.5
			(2.4)			(1.2)
PI 640448	Szechwan 3	1	3.5	1–9	3	1.3
PI 640448	Szechwan 3	2	3.1	1–9	3	1.3
PI 640448	Szechwan 3	3	3.3	1–9	2	1.4
			(3.3)			(1.2)
PI 640461	83–168	1	1.8	1–4	2	0.8
PI 640461	83–168	2	2.2	1–5	2	1.1
PI 640461	83–168	3	2.4	0–9	2	1.1
PI 640461	83–168	4	2.6	1–9	2	1.1
PI 640461	83–168	5	2.4	1–9	2	1.5
PI 640461	83–168	6	1.9	1–7	1	1.0
PI 640461	83–168	7	2.3	1–8	2	1.2
PI 640461	83–168	8	2.1	0–9	1	0.7
			(2.2)			(1.0)
PI 640480	HDA 336	1	1.9	0–3	2	1.1
PI 640480	HDA 336	2	1.8	1–3	2	0.8
PI 640480	HDA 336	3	1.5	0–3	2	0.9
			(1.7)			(0.9)
PI 640516	Chicken Heart	1	1.8	0–5	3	0.7
PI 640516	Chicken Heart	2	3.0	1–9	2	1.7
PI 640516	Chicken Heart	3	2.3	1–9	2	1.1
			(2.4)			(1.2)
PI 640532	871076	1	0.9	0–1	1	0.2
PI 640532	871076	2	1.2	1–2	1	0.2
PI 640532	871076	3	0.6	0–1	0	0.5
			(0.9)			(0.4)
PI 640560	Phyo 636	1	4.3	1–9	3	3.0
PI 640560	Phyo 636	2	2.7	0–3	3	0.3
PI 640560	Phyo 636	3	2.8	1–5	3	1.1
			(3.3)			(1.9)
PI 640581	U-Kimba	1	2.2	0–4	2	0.3
PI 640581	U-Kimba	2	3.3	1–9	2	1.8
PI 640581	U-Kimba	3	3.1	1–9	2	1.4
			(2.9)			(1.2)
PI 640582	UL-2190	1	2.4	1–7	3	1.0
PI 640582	UL-2190	2	2.2	1–4	1	1.2
PI 640582	UL-2190	3	3.1	1–5	3	1.3
			(2.6)			(1.2)
PI 640588	YCb 76105	1	1.3	0–3	1	1.1
PI 640588	YCb 76105	2	3.0	1–9	1	1.6
PI 640588	YCb 76105	3	3.0	0–9	2	3.4
			(2.4)			(2.2)
PI 640641	IR	1	2.0	1–3	2	0.7
PI 640641	IR	3	2.0	1–3	1	0.8
PI 640641	IR	4	2.8	1–9	3	1.0
PI 640641	IR	5	2.7	1–6	2	1.1
			(2.4)			(0.9)
PI 640833	Cascabella	1	0.7	0–1	1	0.4
PI 640833	Cascabella	2	0.6	0–1	1	0.4
PI 640833	Cascabella	3	0.7	0–3	0	1.2
			(0.7)			(0.7)
	Camelot (susceptible control)		9.0	9	9	0.0
	Criollo de Morelos 334 (resistant control)		0.3	0–1	0	0.4

^aLines are selfed seed from individual plants which survived to seed set from the mass screening.

^bBased on a 0 to 9 scale (Bosland and Lindsey, 1991): 0 = no response; 3 = brown roots, slight stunting, very small lesions on stems; 7 = brown roots, large lesions on stems, girdling, whole plant wilted, and stunted; 9 = dead plants. Means are average of four replicates with six plants per replicate. Numbers in parentheses are overall means and sds, respectively, for the accession.

Variation in resistance scores was observed both between lines from an accession as well as between plants within a line. Based on the materials used in the primary screening, it is difficult to attribute these differences to a single factor, i.e., whether it is genetic or not. This variation likely represents a mixture of experimental variability as well as true genetic differences. This, however, does not invalidate the mass screening process but rather results may be specific to only one or a few plants within an accession (as opposed to a more uniform response that might be expected in a homogeneous sample). Many accessions in the USDA's *Capsicum* collections represent landrace cultivar mixtures. Often, accessions were obtained by extracting seed from a purchase of fruit from a local market (Bob Jarret, personal communication) or a collection of landraces from grower fields and would be expected to be genetically heterogeneous. Furthermore, *C. annuum* plants are basically self-pollinating crops (Allard, 1960), but the amount of outcrossing associated with natural insect pollinators is sufficient to impede progress in breeding programs (Bosland, 1993). It was not uncommon to see distinctly different fruit pod types in different plants from the same accession, highlighting the underlying genetic variation of the accession. This variability needs to be addressed to produce homogeneous breeding lines by continuous screening and selection. There are, however, lines and accessions with low or no variability in their resistance to root rot, and these may be primary candidates for breeding programs.

Phytophthora capsici races should be taken into account in subsequent selection processes for these promising accessions because resistance to *Phytophthora* blight may not be effective in different production systems or growing locations. Isolate × genotype interactions for *C. annuum* and *P. capsici* have been demonstrated (Glosier et al., 2008; Oelke et al., 2003). Recently, 14 different physiological races of *P. capsici* were identified from a wide range of sources (Glosier et al., 2008). The variability of the pathogen on vegetable crops in Georgia has not been investigated, but both mating types were present in the samples we obtained locally and races do not appear to be restricted to particular growing regions (Glosier et al., 2008). Lines that were found to be resistant in the greenhouse tests also appeared resistant in the field tests, at least in terms of plant survival. Further screening in other locations, or with other sources of inoculum, will be necessary to assess the value of the germplasm for breeding resistant cultivars targeted to other regions.

The identification of novel sources of resistance, as reported here, may allow the identification of new resistance genes. This would be the first step toward the pyramiding of multiple resistance genes into adapted material to provide resistance to multiple pathogen isolates. However, further screening and selection of these accessions are needed to yield homogeneous materials that

Table 3. The response of *Capsicum annuum* accessions to *Phytophthora* root rot under field conditions.

Accession/variety	Line number ^a	Root discoloration ^b (%)	Plant survival ^c (%)
Camelot (susceptible control)		100.0 a	1.3 c
PI 640527	1	30.4 b	99.3 a
PI 631147	2	29.0 bc	99.3 a
PI 511883	2 + 3	27.7 bcd	95.3 b
PI 640516	2	27.5 bcd	100.0 a
PI 566811	1	27.2 bcde	100.0 a
PI 439321	2	24.7 bcde	99.3 a
PI 640588	1 + 4	24.1 cde	98.7 a
PI 439273	1 + 2	22.4 def	99.3 a
PI 640560	1 + 2	21.4 efg	99.3 a
PI 640532	3	17.5 fg	99.3 a
Criollo de Morelos 334 (resistant control)		16.0 gh	100.0 a
PI 640581	3	11.7 h	99.3 a
PI 593573	3	11.5 h	100.0 a

^aLines are selfed seed from individual plants which survived to seed set from the mass screening. Seeds from two lines within an accession were combined in cases in which seeds from one plant were insufficient for further testing.

^bPercentage of the root system with brown discoloration or rotted. Numbers are averages of five replicates with 20 plants per replicate.

^cSurvival = (number of surviving plants/total number of plants) × 100. Numbers are averages of five replicates with 32 plants per replicate.

can be used in a pepper breeding program. Lastly, the genetic aspects of these resistance sources need to be verified, and the variability among isolates that are responsible for causing each syndrome need to be clarified so that the resistance genes can be effectively used to manage *Phytophthora* blight in a sustainable way.

Literature Cited

- Alcantara, T. and P. Bosland. 1994. An inexpensive disease screening technique for foliar blight of chile pepper seedlings. *HortScience* 29:1182–1183.
- Allard, R. 1960. Principles of plant breeding. 1st Ed. Wiley, New York, NY.
- Babadoost, M. 2004. *Phytophthora* blight: A serious threat to cucurbit industries. APSnet April–May 2004.
- Barksdale, T. 1984. Resistance to foliar blight and crown rot of pepper by *Phytophthora capsici*. *Plant Dis.* 68:506–509.
- Boatright, S. and J. McKissick. 2008. Georgia Farm Gate Vegetable Survey. Center for Agribusiness and Economic Development, College of Agricultural and Environmental Sciences, The University of Georgia, AR-08-01, p. 62–63.
- Bosland, P. 1993. An effective plant cage to increase the production of genetically pure chile (*Capsicum* spp.) seed. *HortScience* 28:1053.
- Bosland, P. and D. Lindsey. 1991. A seedling screen for *Phytophthora* root rot of pepper, *Capsicum annuum*. *Plant Dis.* 75:1048–1050.
- Café-Filho, A. and J. Ristaino. 2008. Fitness of isolates of *Phytophthora capsici* resistant to mefenoxam from squash and pepper fields in North Carolina. *Plant Dis.* 92:1439–1443.
- Erwin, D. and O. Rebeiro. 1996. *Phytophthora* diseases worldwide. American Phytopathological Society, St. Paul, MN.
- French-Monar, R., J. Jones, E. Hanlon, and P. Roberts. 2005. Soil monitoring of viable inoculum of *Phytophthora capsici* localized in soil under vegetable production conditions in southwest Florida. *Fitopatologia* 40:178–187.
- French-Monar, R., J. Jones, and P. Roberts. 2006. Characterization of *Phytophthora capsici* associated with roots of weeds on Florida vegetable farms. *Plant Dis.* 90:345–350.
- Glosier, B., E. Ogundiwin, G. Sidhu, D. Sischo, and J. Prince. 2008. A differential series of pepper (*Capsicum annuum*) lines delineates fourteen physiological races of *Phytophthora capsici*. *Euphytica* 162:23–30.
- Hausbeck, M. and K. Lamour. 2004. *Phytophthora capsici* on vegetable crops: Research progress and management challenges. *Plant Dis.* 88:1292–1303.
- Kelley, W., G. Boyhan, K. Harrison, D. Granberry, P. Sumner, D. Langston, A. Sparks, A. Culpepper, W. Hurst, and E. Fonsah. 2009. Commercial pepper production handbook. Univ. Georgia Res. Bul. 1309.
- Kimble, K. and G. Grogan. 1960. Resistance to *Phytophthora* root rot in pepper. *Plant Dis. Rep.* 44:872–873.
- Kuhajek, J., S. Jeffers, M. Slattery, and D. Wedge. 2003. A rapid microbioassay for discovery of novel fungicides for *Phytophthora* spp. *Phytopathology* 93:46–53.
- Lefebvre, V. and A. Palloix. 1996. Both epistatic and additive effects of QTLs are involved in polygenic induced resistance to disease: A case study the interaction pepper—*Phytophthora capsici* Leonian. *Theor. Appl. Genet.* 93:503–511.
- Leonian, L. 1922. Stem and fruit blight of peppers caused by *Phytophthora capsici*. *Phytopathology* 12:401–408.
- Oelke, L., P. Bosland, and R. Steiner. 2003. Differentiation of race specific resistance to *Phytophthora* root rot and foliar blight in *Capsicum annuum*. *J. Amer. Soc. Hort. Sci.* 128:213–218.
- Ortega, G., C. Palazon Espanol, and J. Cuartero Zueco. 1991. Genetics of resistance to *Phytophthora capsici* in the pepper line ‘SCM-334’. *Plant Breed.* 107:50–55.
- Palloix, A., A. Daubeze, and E. Pochard. 1988. Time sequences of root infection and resistance expression in an artificial inoculation method of pepper with *Phytophthora capsici*. *J. Phytopathol.* 123:12–24.
- Reifschneider, F., A. Café-Filho, and A. Rego. 1986. Factors affecting expression of resistance in pepper (*Capsicum annuum*) to blight caused by *Phytophthora capsici* in screening trials. *Plant Pathol.* 35:451–456.
- Ristaino, J. and S. Johnston. 1999. Ecologically based approaches to management of *Phytophthora* blight of bell pepper. *Plant Dis.* 83:1080–1089.
- Sy, O., P. Bosland, and R. Steiner. 2005. Inheritance of *phytophthora* stem blight resistance as compared to *phytophthora* root rot and *phytophthora* foliar blight resistance in *Capsicum annuum* L. *J. Amer. Soc. Hort. Sci.* 130:75–78.
- Walker, S. and P. Bosland. 1999. Inheritance of *Phytophthora* root rot and foliar blight resistance in pepper. *J. Amer. Soc. Hort. Sci.* 124:14–18.
- Weber, G. 1932. Blight of peppers in Florida caused by *Phytophthora capsici*. *Phytopathology* 22:775–780.