Registration of Pea Germplasm Lines Partially Resistant to Aphanomyces Root Rot for Breeding Fresh or Freezer Pea and Dry Pea Types

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ABSTRACT

Eight germplasm lines of green pea (*Pisum sativum* L.)—RIL 846-07 (Reg. No. GP-99, PI 660729), RIL 847-08 (Reg. No. GP-100, PI 660730), RIL 847-22 (Reg. No. GP-101, PI 660731), RIL 847-28 (Reg. No. GP-102, PI 660732), RIL 847-45 (Reg. No. GP-103, PI 660733), RIL 847-50 (Reg. No. GP-104, PI 660734), RIL 847-53 (Reg. No. GP-105, PI 660735), and RIL 847-68 (Reg. No. GP-106, PI 660736)—were developed and released jointly by the USDA-ARS, the French National Institute for Agricultural Research (INRA), and North Dakota State University. They were selected from an F_8–derived recombinant inbred line (RIL) population developed from a cross between 'Dark Skin Perfection' and 90-2131. These lines all have high levels of partial resistance to root rot caused by *Aphanomyces euteiches* Drechs. f. sp. *pisi* when screened in 12 environments of 10 infested field nurseries across 4 yr and four locations in the USA and France and with two reference isolates in controlled conditions. On the basis of a disease index derived from the 12 environments (location-years), these lines had improved partial resistance compared with either parent. RIL 847-028, RIL 847-050, RIL 847-053, and RIL 847-068 performed better in U.S. field nurseries than in the French nurseries. Conversely, RIL 846-007, RIL 847-008, RIL 847-022, and RIL 847-045 performed better in the French field nurseries than in the U.S. nurseries. The eight lines also have acceptable agronomic characteristics: they have white flowers, straight blunt green pods, and green cotyledons; are clear seeded and semidwarf; and flower at the 14th–16th node in 57–61 d. The release of these germplasms will assist the breeding and development of either smooth- or wrinkle-seeded cultivars for the fresh or freezer pea and dry pea markets, respectively, with improved partial resistance to Aphanomyces root rot.

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Abbreviations: AGI, above-ground index; DSI, disease severity index; QTL, quantitative trait loci; RIL, recombinant inbred line; RRI, root rot index.

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Aphanomyces root rot (caused by *Aphanomyces euteiches* Drechs. f. sp. *pisi*) in peas (*Pisum sativum* L.) is a major constraint limiting pea production worldwide and can cause yield losses up to 100% (Lewis and Gritton, 1992; Persson et al., 1997; Gaulin et al., 2007). *Aphanomyces euteiches* causes severe rotting of the root, cortex, and epicotyl that results in stunting, yellow and wilting leaves, or dead plants (Kraft and Pfleger, 2001). It was first reported in the United States in the 1920s (Jones and Drechsler, 1925) and has since been reported in most pea-growing regions of North America, Europe, Australia, New Zealand, and Japan (Yokosawa et al., 1974; Manning and Menzies, 1980; Persson et al., 1997; Kraft and Pfleger, 2001). No effective fungicides are commercially available. Because the pathogen can survive in the soil up to 10 yr (Papavizas and Ayers, 1974), the only effective control measures include avoiding infested fields and practicing rotations with 4–6-yr intervals.

Resistance to Aphanomyces root rot is quantitative (Shehata et al., 1983), and there are currently no commercially available pea cultivars that have acceptable levels of resistance to the disease coupled with adequate agronomic characteristics. The mechanism of partial resistance has not been elucidated; however, effective screening techniques based on reduced severity of symptoms have been developed to quantify acceptable levels of resistance, which are

referred to as partial resistance (Lewis and Gritton, 1992). Although true races of *A. euteiches* have not been identified in pea, degrees of difference in isolate aggressiveness have been well documented by Wicker and Rouxel (2001) using a set of differential lines (Wicker et al., 2003). Globally, 11 pathotypes have been characterized, and isolates from France tend to be more aggressive than isolates from Scandinavia, North America, or New Zealand (Wicker and Rouxel, 2001). Pathotypes I and III are found in the United States, whereas France is dominated by pathotype I (Wicker and Rouxel, 2001; Wicker et al., 2003). Studies to detect quantitative trait loci (QTL) associated with improved resistance to Aphanomyces root rot (Pilet-Nayel et al., 2002, 2005; Hamon et al., 2011) have also identified highly resistant germplasm lines from different recombinant inbred line (RIL) populations.

Eight pea germplasm lines—RIL 846-07 (Reg. No. GP-99, PI 660729), RIL 847-08 (Reg. No. GP-100, PI 660730), RIL 847-22 (Reg. No. GP-101, PI 660731), RIL 847-28 (Reg. No. GP-102, PI 660732), RIL 847-45 (Reg. No. GP-103, PI 660733), RIL 847-50 (Reg. No. GP-104, PI 660734), RIL 847-53 (Reg. No. GP-105, PI 660735), and RIL 847-68 (Reg. No. GP-106, PI 660736)—have been identified and selected for high levels of partial resistance to Aphanomyces root rot and acceptable horticultural/agronomic characteristics. The F_8–derived lines were selected from a RIL population developed by the USDA-ARS from a cross between the susceptible line 'Dark Skin Perfection' (PI 269772) and the partially resistant line 90-2131 (PI 557501; Kraft, 1992). Dark Skin Perfection is a freezing-type cultivar with white flowers and straight, blunt double pods. It is resistant to Fusarium wilt race 1 [caused by *Fusarium oxysporum*, Schlecht. f. sp. *pisi* (van Hall) Snyd. & Hans.] and is highly susceptible to Aphanomyces root rot. Line 90-2131 is a germplasm release (Kraft, 1992) with white flowers, straight, blunt single pods, a black hilum, and multiple disease resistances. It is resistant to Fusarium wilt races 1, 5, and 6 and to Fusarium root rot [caused by *Fusarium solani* (Mart.) Sacc. f. sp. *pisi* (F.R. Jones) Synd. & Hans.]. Line 90-2131 has partial resistance to Aphanomyces root rot (Kraft 1992). We anticipate that the release of these germplasms will assist in the development of either smooth- or wrinkle-seeded cultivars with improved resistance to Aphanomyces root rot.

Methods

The eight lines are selections from a RIL mapping population derived from the cross Dark Skin Perfection/90-2131. Dark Skin Perfection is a wrinkle-seeded processing pea that was grown commercially between about 1950 and 1970 (Asgrow Seed Co., Kalamazoo, MI). It has white flowers, normal leaves (i.e., leaflets plus tendrils), wrinkled green seeds, and a clear hilum and seed coat. It is susceptible to Aphanomyces root rot. Line 90-2131 is a breeding line developed by the USDA-ARS (Kraft, 1992) and has a complex pedigree: 'Small Sieve Freezer'/C-165/3/'Early Perfection 3020'/C-165//PH-91-3/4/74SN4/5/PI 180693. C-165 is a selection from the University of Wisconsin that is resistant to Fusarium wilt races 1 and 2. PH-91-3 and 74SN4 were released by the USDA and are resistant to Fusarium root rot. PH-91-3 is resistant to Fusarium wilt race 2, and 74SN5 is resistant to Fusarium wilt races 1, 2, and 5. PI 180693 is resistant to *A. euteiches*. Line 90-2131 is characterized by white flowers, green cotyledons, a clear seed coat, black hilum, and dimpled seeds. It has partial resistance to Aphanomyces root rot and is resistant to Fusarium root rot and Fusarium wilt races 1, 5, and 6 (Kraft, 1992). The two parental lines flower at similar nodes (15th–16th node), thus reducing possible bias during scoring for resistance due to maturity differences.

The cross X94P275 was made in 1994, and six F_1 seeds from one pod were the progenitors of the F_2 population. The RIL population was advanced from the F_2 through the F_8 in the greenhouse by single-seed descent. The lines were planted for seed increase at the Washington State University Spillman Agronomy Farm near Pullman, WA in 2000.

The eight partially resistant lines were identified by screening the population in disease nurseries in 10 field environments: two locations across 4 yr in the USA and two locations across 2 yr in France. An RCBD with three replications per entry was used each year at each location. The population was also screened under controlled conditions using the reference isolates RB84 and Ae109 of *A. euteiches* (Moussart et al., 2007). $F_{8:9}$, $F_{8:10}$, and $F_{8:11}$ seeds from the 111 RILs, the two parents, and check lines were evaluated in the disease nurseries severely infested with *A. euteiches* in Le Sueur, MN (44°27′ N, 93°54′ W) in 2000, 2001, 2002, and 2003; Pullman, WA (46°43′ N, 117°10′ W) in 2000 and 2003; Riec-sur-Belon, France (47°50′ N, 3°42′ W) in 2002 and 2003, and Dijon, France (47°19′ N, 5°03′ E) in 2002 and 2003. The soils at each of the nurseries were characterized as a clay loam at Le Sueur, a silty loam at Pullman, a well-drained sandy silt at Riec-sur-Belon, and a clay loam at Dijon. The partially resistant checks included in all the nurseries were PI 180693 (Lockwood, 1960) and '552' (Gritton, 1995). The susceptible checks included Puget (Brotherton Seed, Moses Lake, WA) and Baccara (Florimond Desprez, Cappelle-en-Pévèle, France) in the U.S. nurseries and Capella (Svalöf Weibull AB, Malmo, Sweden) and Baccara in the French nurseries. Verification of the presence of *A. euteiches* in the Le Sueur, MN and Pullman, WA nurseries was done with the wet sieve method (Kraft and Boge 1996) and through the disease symptoms on roots and the aboveground plant reaction of appropriate check cultivars (listed above) in the Dijon nursery. An extensive bioassay-based study of the special distribution of *A. euteiches* inoculum was conducted at the Riec-sur-Belon nursery (Moussart et al., 2009). Each plot in each replicate consisted of either 2-m-long single rows in the U.S. nurseries or 2-m-long twin rows in the French nurseries. Each row had 30 plants. Cultural practices were consistent with local production guidelines. The lines were sown each spring and evaluated for disease severity in early summer at the start of flowering and approximately 2 wk later during early pod fill. The nurseries in Pullman, Riec-sur-Belon, and Dijon were irrigated as needed to ensure development of Aphanomyces root rot. The Le Sueur nursery received adequate rainfall and was not irrigated.

In the U.S. nurseries, the above-ground index (AGI) for disease severity of each plot was rated on a 0–5 scale (0 = disease free; 5 = severely infested; Pilet-Nayel et al., 2002) at all locations and years. In the French nurseries, a 1–9 scale (1 = disease free; 9 = completely infested) was used to rate the AGI on each plot (Duparque and Boitel, 2001, modified from Lewis and Gritton, 1992). The AGI was scored at full bloom (AGI1) and approximately 2 wk later (AGI2). Additionally, in the French nurseries, the root health of each plot was assessed. A root rot index (RRI) score was taken when the plants were at the seventh node above the cotyledons. Ten plants per plot were scored on a 0–5 scale (0 = healthy, all roots white; 5 = plant dead; Moussart et al., 2001). The mean RRI score of the 10 plants was the calculated RRI for each plot.

The population, parents, and check lines were also screened in controlled environments in growth chambers with the French reference isolate RB84 (Moussart et al., 2007) and the U.S. reference isolate Ae109 (also called Ae467; Makvick et al., 1998). RB84 was isolated from an infested pea field near Riec-sur-Belon, France. It is very aggressive on pea and belongs to the main virulence group (pathotype I) in France (Wicker and Rouxel, 2001). Ae109 was isolated from an infested pea field in Wisconsin and belongs to the main virulence group (pathotype III) in the USA (Wicker and Rouxel, 2001). A standardized evaluation protocol for evaluating resistance to *A. euteiches* in controlled conditions was followed (Moussart et al., 2001, 2007). Four replications of five plants per genotype were inoculated with 10^3 zoospores/plant. Seven days after inoculation, the plants were extracted from the flats, the root systems were vigorously washed in tap water, and the plants were visually scored for disease severity on a scale of 0—5 as follows: 0 = no visible symptoms; 1 = a few small discolored lesions on the entire root system; 2 = minor discoloration on entire root system; 3 = brown discoloration on entire root system, but no symptoms on epicotyl or hypocotyl; 4 = brown discoloration on entire root system, and shriveled and brown epicotyl or hypocotyls; and 5 = dead plant.

Data were analyzed with SAS 9.2 (SAS Institute, Cary, NC). Differences between lines were determined by analysis of variance using the PROC GLM module of SAS detailed by Hamon et al. (2011). To combine the disease severity scores of each RIL from different environments, different rating criteria (AGI1, AGI2, and RRI) and different scoring systems, the score least squares means were normalized with the formula:

$$x_{ij} = \left(x_{ij} - \overline{X}_j\right) \Big/ \sigma_j$$

(Steel and Torrie, 1980), where x_{ij} is the disease score of the *i*th entry in the *j*th environment, $\overline{X}_j$ is the grand mean of all entries in the *j*th environment, and σ_j is the standard deviation for the *j*th environment. For each RIL, a disease severity index (DSI) was then calculated as

$$\mathrm{DSI} = \sum \left[\left(x_{ij} - \overline{X}_j\right) \Big/ \sigma_j \right]$$

Separate disease severity indices were calculated for the combined French nurseries and for the combined U.S. nurseries. A third DSI was calculated as the sum of the French index and the U.S. index and was called the global index. For each DSI, equal weight was given to each environment. Lines with larger negative index scores are more resistant to Aphanomyces root rot than are lines with index scores close to 0 or positive.

Characteristics

Plants of the eight lines are characterized as having normal leaves and white, unpigmented flowers. The lines are all of similar maturity (57–61 d to first flower at the 14th–16th node), height (34–45 cm) and are determinate (semidwarf). The pods of all the selected lines are straight, blunt, and green with well-formed seed. The seeds of the lines have clear seed coats and green cotyledons. Seed characteristics of two of the germplasm lines, RIL 847-22 and RIL 847-53, will be most useful for breeding processing-pea types that are harvested when immature for the fresh, frozen, and canning industries. The other six germplasm lines—RIL 846-07, RIL 847-08, RIL 847-28, RIL 847-45, RIL 847-28-50, and RIL 847-68—will be most useful for breeding in the dry pea programs, targeting either the dry edible market or the feed market. Seed characteristics of the germplasm releases and the parents are summarized in Table 1.

When the population was screened in controlled conditions with the two reference isolates, their relative virulence on the distribution of the performance of the RILs was observed. When the population was screened with Ae109, RRI adjusted mean scores had a normal distribution; however, the RRI adjusted mean scores had a bimodal distribution when screened with RB84 (Fig. 1). The mean-based heritability of the RB84 RRI was high ($h^2 = 0.91$) compared with the moderate heritability of the Ae109 RRI ($h^2 = 0.67$). These results agree with the distribution patterns and heritability estimates we obtained when two other RIL populations were screened with these isolates (Hamon et al., 2011).

We devised a global index to identify the lines with the best partial resistance across multiple environments and

Table 1. Seed characteristics of green pea germplasm releases and parents with partial resistance to Aphanomyces root rot grown in four French and six U.S. environments.

Line	Seed shape	Growth habit	Cotyledon color	Hilum color	Seed weight
					g/100 seeds
Dark Skin Perfection	wrinkled	semidwarf	green	clear	19.5
90-2131	dimpled	semidwarf	green	black	21.8
RIL 846-07	dimpled	semidwarf	green	black	20.3
RIL 847-08	dimpled	semidwarf	green	black	17.2
RIL 847-22	wrinkled	semidwarf	green	clear	21.5
RIL 847-28	dimpled	semidwarf	green	black	20.4
RIL 847-45	dimpled	semidwarf	green	clear	19.3
RIL 847-50	dimpled	semidwarf	green	black	23.0
RIL 847-53	wrinkled	semidwarf	green	black	22.1
RIL 847-68	dimpled	semidwarf	green	black	22.7

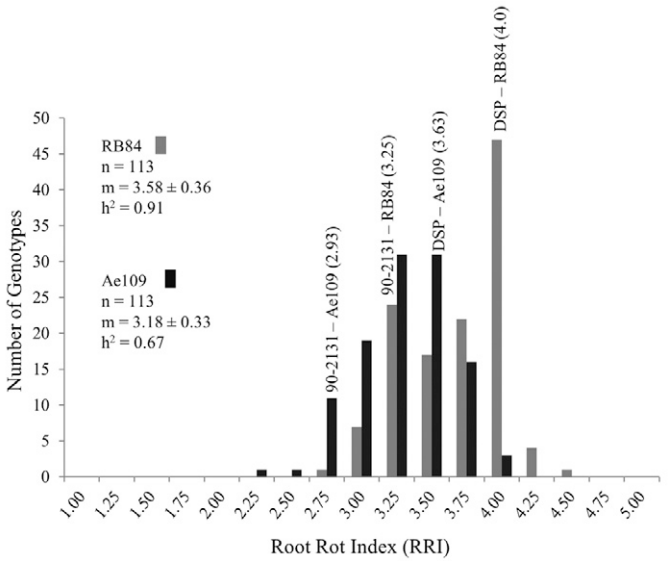

Figure 1. Frequency distribution of adjusted mean root rot index scores of 113 lines screened for resistance to two reference isolates, RB84 (black bars) and Ae109 (gray bars), of *A. euteiches* under controlled conditions. When screened with RB84, the mean root rot index (RRI) of 90-2131 was 3.25 and of Dark Skin Perfection was 4.0. When screened with Ae109, the mean RRI of 90-2131 was 2.93 and of Dark Skin Perfection was 3.63. m = mean ± standard deviation of the RIL population.

resistance criteria. Additionally, we constructed separate indices from the French and U.S. nurseries to identify any lines that had higher levels of partial resistance to either of the endemic pathogen populations. The susceptible parent, Dark Skin Perfection, was highly susceptible to Aphanomyces root rot in all 10 field environments. Although 90-2131 had partial resistance to *A. euteiches* in the U.S. nurseries, it was susceptible in the French nurseries. The resistance of the selected lines exceeds that of 90-2131 based on the global index, which was used to identify the best lines to release internationally to breeders. The frequency distribution (Fig. 2) of the adjusted mean scores in the global index indicates that the disease resistance of the lines is distributed continuously in a bimodal fashion. There are some transgressive segregants that are more resistant than 90-2131 and some that are more susceptible than Dark Skin Perfection. The transgressive segregants that were more resistant to Aphanomyces root rot than the resistant parent, 90-2131, were selected. Even though Dark Skin Perfection is highly susceptible to Aphanomyces root rot, previous work has detected QTL in Dark Skin Perfection associated with partial resistance (data not presented). The transgressive segregants that are better than 90-2131 in the French environments probably carry this QTL. Analysis of variance of the AGI in each nursery revealed highly significant genotypic effects (P ranging from 0.0315 to <0.0001). Similarly, there were significant genotypic effects for RRI ($P < 0.015$). Mean-based heritabilities of the resistance traits ranged from 0.25 (Riec-sur-Belon, AGI1, 2003) to 0.87 (Pullman, AGI1, 2003). Lower heritability values were mostly observed for field RRI and AGI1.

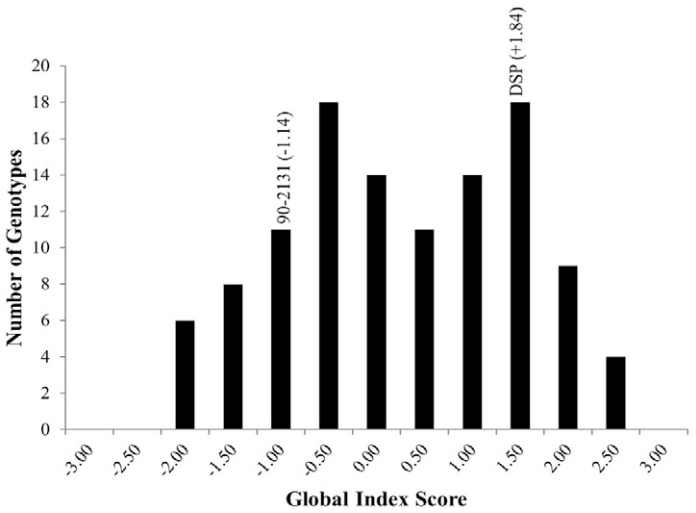

Figure 2. Frequency distribution of global index scores of 113 lines and the parents of RIL population Dark Skin Perfection × 90-2131 evaluated in field nurseries in France and USA. The global index value of 90-2131 was −1.14 and of Dark Skin Perfection was +1.84. Values of the eight selected lines ranged from −1.66 to −2.42.

When the global index was used, the lines selected for release had higher levels of partial resistance to Aphanomyces root rot than either parent. The pathogenic variability of *A. euteiches* has been documented within both the USA (Malvick and Percich, 1998; Grünwald and Hoheisel, 2006) and France (Wicker and Rouxel, 2001), and French isolates tend to be more aggressive on pea than are isolates from the USA (Wicker and Rouxel, 2001). RIL 847-28, RIL 847-50, RIL 847-53, and RIL 847-68 performed better in U.S. field nurseries than in the French nurseries. Conversely, RIL 846-07, RIL 847-08, RIL 847-22, and RIL 847-45 performed better in the French field nurseries than in the U.S. nurseries (Table 2).

Availability

These germplasms are expected to be used as parental material in the development of cultivars with improved resistance to Aphanomyces root rot and resistance to Fusarium wilt race 1. Seed will be deposited in the National Plant Germplasm System, where it will be available immediately for research purposes, including development and commercialization of new cultivars. Seed may be obtained from the Western Regional Plant Introduction Station (http://www.ars.usda.gov/pwa/pullman/wrpis). There are no restrictions on their use in breeding for pea variety improvement. It is requested that appropriate recognition be made if this germplasm contributes to the development of new breeding lines and/or cultivars.

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Table 2. Disease severity indices based on normalized least squares means of the parents, checks, and selected recombinant inbred lines screened for partial resistance in four French and six U.S. environments.†

Entry	Market class	French index‡	U.S. index§	Global index¶
Parents				
Dark Skin Perfection	fresh or freezer type	+0.56	+1.28	+1.84
90–2131	dry edible	+0.55	–1.69	–1.14
Checks				
Baccara	dry edible	+0.93	+2.17	+3.10
Capella	dry edible	+0.47	+1.93	+2.40
'552'	fresh or freezer type	–1.36	–0.28	–1.64
PI 180693	—#	–1.18	–0.55	–1.73
Selections				
RIL 846-07	dry edible	–1.30	–0.74	–2.04
RIL 847-08	dry edible	–1.44	–0.98	–2.42
RIL 847-22	fresh or freezer type	–1.14	–0.69	–1.83
RIL 847-28	dry edible	–0.91	–1.04	–1.95
RIL 847-45	dry edible	–1.44	–0.67	–2.11
RIL 847-50	dry edible	–1.16	–1.20	–2.36
RIL 847-53	fresh or freezer type	–0.77	–0.89	–1.66
RIL 847-68	dry edible	–0.94	–1.39	–2.33

†Lines with larger negative index scores are more resistant to Aphanomyces root rot than are lines with index scores close to 0 or positive.

‡Calculated from French disease nurseries.

§Calculated from U.S. disease nurseries.

¶Sum of the French and USA indices.

#Unacceptable for any market class.

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