Resistance to *Phytophthora* Root Rot Varies among *Rhododendrons* Subjected to Repeated Flooding in the Field

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Abstract

A replicated field trial containing *Rhododendron* cultivars, species, and experimental hybrids was repeatedly flooded during one growing season to test for resistance to *Phytophthora cinnamomi* under stress conditions. At the end of the season root rot disease scores were assigned based on visual assessment of root, crown, and shoot necrosis using a numerical rating scale of 1 (healthy fine roots) to 5 (dead plant). Under flooding conditions, the average disease score of three resistant cultivars (controls used as benchmarks) was 4.1, which was a 90 percent increase above their previously determined average of 2.2 under non-flooded conditions. In contrast, disease scores of the resistant species *R. hyperythrum* were 35 percent higher under flooded (2.7) than non-flooded (2.0) treatments. Eight F_1 hybrids derived from *R. hyperythrum* had an average disease score of 3.3 and were significantly less diseased than the resistant benchmark cultivars under flooded field conditions. Loss of root rot resistance in flooded soils could result from conditions that favor pathogen development and infection and from physiological changes in host plants that predispose them to disease. Under flooding conditions, *R. hyperythrum* appears to be less predisposed to root rot than resistant genotypes with different genetic backgrounds. While the basis for this difference in stress response is not currently known, it appears to be heritable in the F_1 generation and represents a valuable trait for root rot resistance breeding.

INTRODUCTION

Root rot caused by the invasive soil fungus *Phytophthora cinnamomi* is a major source of mortality in *Rhododendron* and many other popular ornamental genera (Benson and Broembsen, 2001). The pathogen may also restrict the natural occurrence or horticultural use of *Rhododendron* species and cultivars in southern regions. *Phytophthora cinnamomi* is more problematic in warmer climates because it is susceptible to frost and thrives in warm, wet soils (Brasier, 1996; Marcais et al., 1996), and epidemiologists predict that global warming will increase the activity of the pathogen (Anderson et al., 2004; Bergot et al., 2004; Brassier, 1994).

In container production, the disease can be effectively controlled through the use of well-drained and suppressive bark mixes (Hoitink and Schmitthenner, 1977), fungicide drenches (Benson, 1985, 1986), and chlorine treatment of irrigation water (Hong, 2003). Preventative options are much more limited for growers and consumers who field-plant rhododendrons, where proper siting of plants and soil amendment strategies to provide good drainage are the primary lines of defense. Furthermore, many homeowners plant in substandard soils without knowledge of these basic cultural methods for disease prevention.

Genetically-conferred host resistance to *P. cinnamomi* offers an additional layer of defense against the pathogen. Among some *Rhododendron* subgenera – notably *Tsutsusi* (evergreen azaleas) – resistance is found at relatively high frequency (Benson, 1980), which may explain why this group of plants thrives in the warmer regions of the USA (e.g., the Gulf South). In contrast, resistance among large-leafed, elepidote rhododendrons (subgenus *Hymenanthes*) occurs at less than 3% frequency (Hoitink and Schmitthenner,

1974; Krebs and Wilson, 2002), and garden use of this group is restricted to more northern, cooler regions of the USA. A notable exception is the elepidote species *R. hyperythrum* from Taiwan – it is resistant to root rot and both the species and hybrids derived from it perform well in southern Louisiana (Thornton, 1990).

Recently, a new breed of rhododendrons has been introduced with the potential to overcome some of the limitations posed by root rot disease and warm climates to successful plant culture. Plant Development Services, Inc. (PDSI®) and Southern Living® magazine have introduced five *R. hyperythrum* hybrids from Dr. John Thornton's Louisiana breeding program (www.azaleachapter.com/gulf_south.htm) into their Southern Living Plant Collection® under the Southgate™ brand. These rhododendrons have novel heat tolerance and are targeted for USDA hardiness zones 6-9. Because *R. hyperythrum* is also known to be resistant to *P. cinnamomi*, it is possible that the hybrids derived from it have some resistance. However, formal tests of root rot resistance were not part of the original field evaluations.

Root rot resistance in rhododendrons is not immunity to the disease, but more aptly termed a 'partial' resistance that often is adequate for conferring defense against *P. cinnamomi* under field conditions. However, environmental conditions, particularly stresses such as drought, flooding, heat, and salinity, can weaken host resistance to plant pathogens, a phenomena referred to as 'induced susceptibility' or 'predisposition' to disease caused by abiotic stress (Blaker and MacDonald, 1981; MacDonald, 1982a, 1991). This study was initiated to test field levels of root rot resistance in the new southern rhododendron introductions and to test whether resistance is maintained under stressful conditions. In this experiment, soils were repeatedly flooded to promote pathogen development and to determine whether flooding stress predisposed the test plants to root rot disease. The results from these extreme conditions confirm that *R. hyperythrum* and its hybrids are resistant to *P. cinnamomi* and less predisposed to disease than other resistant rhododendrons under flooding conditions.

MATERIALS AND METHODS

Plants

Twenty-four rhododendrons were included in the field trial (Table 1). All but two are elepidote, non scaly leafed rhododendron hybrids – exceptions are the lepidote (scaly leafed) cultivar *R.* 'PJM Elite' and the elepidote species *R. hyperythrum.* The group included nine root rot susceptible genotypes and four resistant genotypes that had previously been tested in greenhouse screens (Hoitink and Schmitthenner, 1974; Krebs and Wilson, 2002). These served as experimental controls to and as benchmarks for comparing the disease response in 11 unknown genotypes, nine of them F_1 *R. hyperythrum* hybrids from Dr. Thornton's southern breeding program (including five Southgate™ introductions) and two previously untested cultivars from other breeding programs (Table 1). Propagation of plants was done either conventionally (rooted cuttings) or by tissue culture at Briggs Nursery, Ltd., and plants in both cases were grown outdoors for one season in 4" pots containing 2:3, vol:vol, peat:perlite with the addition of low-rate, slow release fertilizer (Polyon® 21-7-16 at 1.1 L/m^3). Prior research has shown that tissue-culture has no effect on disease ratings (Krebs and Wilson, 2002).

Field Culture and Flooding Treatment

The rhododendrons were planted in a randomized complete block field design with five replications (blocks) in fall 2010 at the David G. Leach Research Station of The Holden Arboretum in Madison, Ohio. Native soils at that location are acid sandy loams with a seasonal high water table at ~457 mm depth in late winter and spring, but well drained and requiring irrigation of shallow-rooted plants such as rhododendrons during the summer. The selected field was one where rhododendrons with symptoms consistent with root rot disease had been previously observed. Soil was removed to create a level planting surface several inches below grade that could be flooded either by heavy rainfall or by

pumping water into it. The plot was mulched with composted wood chips after planting, and the following spring (2011) it received a one-time fertilizer application (Green Magic, 18-6-12 at 1 kg/100 m^2). Due to record rainfall in 2011, it was not necessary to pump water into the site – it was flooded at least eight times during the growing season (April-October) with water covering the root systems for 1-2 days before draining.

Disease Ratings

Beginning in May 2011, plant mortality was recorded monthly in the field from plants exhibiting leaf wilting symptoms characteristic of advanced root rot disease. The experiment was concluded in October 2012, at which time the overall mortality rate was 40%. Surviving plants were dug from the field so that their roots could be washed and evaluated. This involved using pruning shears to cut into crown and coarse root tissue so that the extent of root rot necrosis could be observed in cross sections. Disease scores were assigned using numerical value from 1-5 based on a visual assessment of the extent of symptoms; 1 = healthy roots, 2 = fine root necrosis, 3 = coarse root necrosis, 4 = crown rot, 5 = dead plant (Hoitink and Schmitthenner, 1974; Benson, 1980; Krebs and Wilson, 2002). Two-way analysis of variance (ANOVA, IBM© SPSS© Statistics) was performed on disease scores using genotype and block as the main effects. Subsequent paired comparisons of key groups of plants were made using t-tests.

Confirmation of Pathogen

Putative isolates of *P. cinnamomi* were established from symptomatic root and crown tissue of several field plants using semi-selective PARPH-V8 media (Ferguson and Jeffers, 1999). Briefly, thin slices of tissue from necrotic regions were surface sterilized for one minute in a 0.5% sodium hypochlorite solution followed by three sequential rinses in sterile distilled water. After blotting dry on autoclaved paper towels, the slices were embedded in the PARPH-V8 agar and cultured at 25°C in the dark for one week. Mycelium growing on the surface of the agar had a white, aerial appearance typical of *P. cinnamomi* colonies, and microscopic examination confirmed the presence of chlamydospores and a coralloid growth pattern with abundant hyphal swellings consistent with that species. Subsequently, cultures from different plant and tissue sources were transferred to fresh plates of PARPH-V8, checked for bacterial contamination, and used to extract DNA for amplification and molecular confirmation. PCR followed the protocols developed by Kong et al. (2003) using primer pairs specific for the *Lpv*3 putative storage protein gene in *P. cinnamomi.* PCR products were sent for sequencing at the Plant-Microbe Genomics Facility at The Ohio State University.

RESULTS

Flooding treatments in this experiment proved less controlled than anticipated due to record precipitation in 2011 (1658 mm, 163% above average), including several intense rainfall events of 51-76 mm/day during the growing season (http://www.erh.noaa.gov/cle/). Normally, with average precipitation and well-drained soils that lower the water table throughout the growing season, the frequency and of duration of field flooding events would have been more precisely achieved by pumping water into the field site. As a result, the severity of the flooding stress was greater than had been planned.

Advanced root rot symptoms (plant wilting) were observed in susceptible control plants beginning in late May 2011. By the end of the field trial in October 2011 the overall mortality rate was 40%. Many of the surviving plants exhibited leaf chlorosis that suggested some degree of stress due to flooding and/or pathogen exposure (Figure 1). The presence of *P. cinnamomi* in symptomatic roots and crown tissue taken from field plants was confirmed with near certainty by DNA sequence matches to the LPV3 putative storage protein gene from that species. Of 5 isolates taken from different genotype and tissue sources, three resulted in PCR products with long enough sequences (66-76% coverage) to predict 96-100% identity.

Disease scores ranged from 2.7 (*R. hyperythrum*) to 5.0 (a group of 4 cultivars that died early in the field trial). The overall mean disease score in the flooding experiment was 4.0 (Table 1), indicating that root rot had advanced into the crown tissue of most plants. As expected, most of the susceptible controls died (average disease score = 4.8, Table 2). The exception was *R.* 'Chionoides', a cultivar previously listed as susceptible (Hoitink and Schmitthenner, 1974) but appearing among the most resistant in this trial (Table 1). ANOVA revealed significant effects of genotype and block on disease scores, but not for the interaction of genotype x block (data not shown). Using the LSD value of 1.1 ($P < 0.05$), *R. hyperythrum* and several hybrids derived from it were significantly more resistant than half of the genotypes tested.

Three cultivar "benchmarks" – genotypes that had proven resistant in prior research using controlled inoculations of potted plants in the greenhouse – were susceptible under flooding conditions in the field (Tables 1 and 2). The average disease score for 'Caroline', 'Disca', and 'Ingrid Mehlquist' in the field (4.2, equivalent to crown damage) represented a 90% increase from their average score determined by greenhouse inoculations (2.2, disease limited to fine roots). In contrast, the field disease score of the resistant species *R. hyperythrum* (2.7) represented a 35% increase from its rating in greenhouse trials. Both *R. hyperythrum* and the nine F_1 hybrids derived from it (mean disease score =3.3) were significantly more resistant under flooded conditions than the three resistant benchmarks (Table 2).

DISCUSSION

The field experiment was designed to test root rot resistance under stressful but controlled flooding conditions. However, record rainfalls during the 2011 season resulted in more frequent and extended periods of flooding than planned, and this raises the issue of hypoxic or anoxic soil conditions on plant health. Separating low O_2 from fungal parasites as causes for root damage and plant mortality is made difficult by the fact that the necessary controls (flooded but not inoculated, inoculated but not flooded) were not possible under field conditions. However, in experiments that have used containerized *Rhododendron*, *Malus*, and *Eucalyptus* to separate the effects of flooding versus flooding plus inoculum (*Phytophthora*), flooding stress alone generally results in no mortality and a minimal reduction in plant growth (Blaker and MacDonald, 1981; Wilcox, 1993; Burgess et al., 1999).

In the field trial, the temporal sequence and final distribution of plant mortality among rhododendron genotypes is more consistent with a biotic (pathogen) than abiotic (hypoxia) role in the outcome. Susceptible controls died early in the season (beginning in late May), while some resistant controls (e.g., the three cultivar benchmarks) exhibited disease symptoms much later in the season. At the end of the experiment, the largest group of survivors included the resistant species *R. hyperythrum* and previously untested hybrids derived from it. Finally, the presence of *P. cinnamomi* in symptomatic tissue was confirmed in a small sample of field plants by culture on selective media, morphology, and DNA sequence homology.

The results demonstrate that *P. cinnamomi* resistance in diverse rhododendrons is attenuated by flooding conditions, but to varying degrees depending on the plant genotype.

Repeated flooding of the three resistant benchmark cultivars resulted crown necrosis or mortality. One of these cultivars – *R.* 'Caroline' – was used in previous research to demonstrate that 24-48 hours of flooding (and drought) treatment can predispose plants to disease caused by *P. cinnamomi* (Blaker and MacDonald, 1981). In these experiments, application and removal of the stress prior to inoculation demonstrated that a change in the host response had occurred which rendered it susceptible to root rot disease. Other abiotic stresses, including salinity (MacDonald, 1982b; Matthew et al., 2010) and temperature (MacDonald, 1991; Koga et al., 2004) have been shown to have a similar ability to induce susceptibility in plants. Predisposition has been linked to an increase in abscisic acid (ABA) levels following stress treatment, which in turn

suppresses the salicylic acid signaling pathway required for the expression of many defense genes (Koga et al., 2004; Mohr and Cahill, 2007; Matthew et al., 2010). Exogenous application of ABA to plant tissues mimics the predisposition to disease caused by abiotic stresses (Koga et al., 2004; Matthew et al., 2010).

Loss of resistance in the field trial could have also resulted from flooding conditions that directly favored pathogen development and infection and increased the disease pressure on plants with weakened defense systems. Soil moisture near saturation promotes sporangia development, zoospore release and movement (by flagella), and subsequent infection of host root tips (Benson, 1986; Ownley and Benson, 1991). Disease severity in *Persia indica* caused by *P. cinnamomi* was shown to increase in soils with high matric potential (Sterne et al., 1977), presumably due to increased pathogen activity.

In contrast to the cultivar benchmarks, the resistant species *R. hyperythrum* and some F_1 hybrids derived from it were significantly less diseased at the end of the field trial. The range of disease scores among F_1 s varied from plants nearly as resistant as the *R. hyperythrum* parent ('Trilby × *R. hyperythrum*', *R.* 'Radiance™', *R.* 'Charles Loomis') to others that were more susceptible, such as *R.* 'Brandi™'. Segregation for *P. cinnamomi* resistance has been observed in *Rhododendron* F_1 populations (Krebs, 2009) and is not unexpected due to the high level of heterozygosity in outcrossing woody plants (Hamrick and Godt, 1996). *Rhododendron hyperythrum* has a relatively high breeding value for resistance breeding, and resistance can be recovered in 10-20% of F_1 segregants depending on the other parent in the cross (Krebs, 2009).

High root rot resistance and lower predisposition to disease under flooding stress add to a number of attributes *R. hyperythrum* provides as a breeding parent. In addition to being 'heat tolerant' – one of only a few elepidote species capable of growing in the Gulf South (USDA hardiness zone 8) – it has some cold hardiness (USDA zone 6), a compact, dense growth habit, glossy dark green leaves, and a floriferous nature that derives from an abundance of axillary shoots forming from buds subtending current year flowers. Its primary ornamental shortcomings are white flowers arranged in a loose inflorescence rather than the preferred pyramidal or 'ball' shape. At The Holden Arboretum, crosses between *R. hyperythrum* and cold hardy (USDA zone 5) cultivars with saturated flower colors have produced vigorous and attractive F_1 hybrids that are being evaluated for root rot resistance and adaptation to both northern and southern U.S. growing conditions.

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Tables

Table 1. Root rot disease scores for 24 *Rhododendron* genotypes included in the 2011 field flooding trial.

Genotype	N	Mean disease score[1]	SD	Classification[2]	Source[3]
R. hyperythrum	5	2.7	0.4	R[4,5]	B
R. 'Trilby' × *R. hyperythrum*	5	2.8	0.8	UH	R
R. 'Charles Loomis'	5	3.0	1.2	UH	B
R. 'Radiance™'	5	3.0	1.0	UH	B
R. 'Chionoides'	5	3.2	1.3	S[4]	B
R. 'Divine™'	5	3.2	0.4	UH	B
R. 'Disca' × *R. hyperythrum*	4	3.3	1.3	UH	R
R. 'Grace™'	4	3.3	1.3	UH	B
R. 'Peppermint Twist'	4	3.5	1.3	UH	B
R. 'Breezy™'	4	3.8	1.0	UH	B
R. 'Caroline'	5	3.8	1.3	R[4,5]	R
R. 'Mardis Gras'	5	3.8	0.4	UNH	B
R. 'Calsap'	5	4.0	1.0	UNH	R
R. 'Ingrid Mehlquist'	4	4.3	1.0	R[5]	B
R. 'Brandi™'	5	4.4	0.9	UH	B
R. 'Disca'	5	4.4	0.9	R[4]	R
R. 'Roseum Elegans'	5	4.4	0.9	S[4]	B
R. 'Purpureum Elegans'	5	4.6	0.9	S[4]	B
R. 'Roseum Pink'	5	4.6	0.5	S[4]	B
R. 'Nova Zembla'	5	4.8	0.4	S[4]	B
R. 'Catawbiense Album'	5	5.0	0.0	S[4]	B
R. 'Edith Bosley'	5	5.0	0.0	S[4]	B
R. 'Haaga'	4	5.0	0.0	S[4]	B
R. 'PJM Elite'	5	5.0	0.0	S[4]	B
Total	114	4.0	1.1		
LSD ($P < 0.05$)		1.1			

[1] Extent of root rot based on a visual assessment of symptoms, where 1 = healthy roots, 2 = fine root necrosis, 3 = coarse root necrosis, 4 = crown rot, 5 = dead plant. See materials and methods for further detail.

[2] Known resistance phenotypes at time of experiment. R = resistant, S = susceptible, UH = untested *R. hyperythrum* hybrid, UNH = untested non-*R. hyperythrum* hybrid. Number superscripts refer to reports in 4 (Hoitink and Schmitthenner, 1975) and 5 (Krebs and Wilson, 2002).

[3] Source of plant was either B (tissue cultured from Briggs Nursery, Ltd.) or R (cuttings rooted by Van Veen Nursery).

Table 2. Comparisons of disease responses under flooded and non-flooded conditions, and tests of significant mean differences among groups of flooded plants.

Test group	N	Mean root rot score Non-flooded [2]	Mean root rot score (S.E.) Flooded [3]
Susceptible cultivars[1]	8	4.9	4.8 a (0.08)
Resistant cultivars (benchmarks)	3	2.2	4.1 b (0.28)
R. hyperythrum F_1 hybrids	9	na	3.3 c (0.16)
R. hyperythrum	1	2.0	2.7 c (0.20)

[1] *R.* 'Chionoides' was omitted because although it was reported susceptible in a previous report it appeared resistant in this trial.
[2] Mean root rot scores from previously published disease screens; (Hoitink and Schmitthenner, 1975; Krebs and Wilson, 2002).
[3] Means followed by the same letter are not significantly different (*t*-test, $P < 0.05$).

Figures

Fig. 1. View of field trial in fall 2011, following multiple flooding events during the growing season. Overall mortality at this point was 40%.

Fig. 2. Cross section of root and crown tissue of *R.* 'Grace™' (left) showing intact crow tissue and discoloration of coarse roots (arrow) symptomatic of root rot (disease score = 3). In *R.* 'Disca' (right), disease symptoms are more advanced and evident in both the crown tissue and lower stem (disease score = 5).