Fungicide Efficacy in Prevention of Root Rot Incited by *Phytophthora cactorum* and *Phytophthora drechsleri* in Fraser Fir Seedlings

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SUMMARY. The most serious disease problem in fraser fir (*Abies fraseri*) Christmas tree production is phytophthora root rot (PRR). The efficacies of six fungicide treatments in preventing PRR incited by *Phytophthora cactorum* and *P. drechsleri* in 2-year-old fraser fir seedlings were evaluated in 2010 and 2011 in central Pennsylvania. The study examined five fungicide drench treatments [dimethomorph, fosetyl-aluminum (fosetyl-Al), hydrogen dioxide, mefenoxam, propamocarb hydrochloride] and one soil spray treatment (mefenoxam) in raised planting boxes. Dimethomorph applied on 14-day intervals prevented foliar disease symptoms and mortality in fraser fir seedlings exposed to either *P. cactorum* or *P. drechsleri*. One-time application of fosetyl-Al or mefenoxam were effective at times in preventing foliar disease symptoms and mortality in fraser fir seedlings exposed to *P. drechsleri* but were not as effective against *P. cactorum*.

Fraser fir is a valuable cut Christmas tree crop in the eastern United States, particularly in North Carolina, Michigan, and Pennsylvania (Tompkins, 2000; Williams, 2002). The species is preferred because of its fast and consistent growth habit and excellent postharvest durability (Mitcham-Butler et al., 1988). In 2010, fraser fir accounted for ≈26% of the planted cut Christmas tree crop in Pennsylvania, second only to douglas fir (*Pseudotsuga menziesii*) which accounted for ≈42%. On a per tree basis fraser fir is estimated to be 15% more valuable than douglas fir in Pennsylvania (U.S. Department of Agriculture, 2009). Use of fraser fir is not more prevalent because of its sensitivity to poorly drained soils (Owen, 2005). In poorly drained soils, PRR is the limiting factor in fraser fir production

and is the only serious disease affecting fraser firs in Pennsylvania.

Multiple species of *Phytophthora* are known to contribute to root rot in fraser fir (Benson et al., 1976; Kuhlman and Hendrix, 1963; Quesada-Ocampo et al., 2009; Shew and Benson, 1981). Most research has focused on *P. cinnamomi* (Benson and Grand, 2000). In diseased fraser fir specimens sent to the Pennsylvania Department of Agriculture Plant Diagnostic Laboratory between 1986 and 2011, *P. cactorum*, *P. cryptogea*, and *P. drechsleri* were the most common causes of PRR (T. Olson, personal communication). *Phytophthora cryptogea* and *P. drechsleri* have very similar morphology and are usually separated based upon the ability of *P. drechsleri* to grow at 35 °C (Erwin and Ribeiro, 1996; Ho and Jong, 1991; Mostowfzadeh-Ghalamfarsa et al., 2010).

The use of fungicides to prevent PRR in fraser fir production is most common at the seedling stage. The efficacies of various fungicides in preventing PRR in fraser fir have been

tested with *P. cinnamomi*. Bruck and Kenerley (1981, 1983) reported that drench applications of metalaxyl prevented PRR in fraser fir seedlings planted in a soilless substrate in greenhouse and nursery bed settings. Benson and Grand (2000) reported that isolates of *P. cinnamomi* recovered from fraser fir in field settings and nursery transplant beds were sensitive to metalaxyl in plate tests in a laboratory setting. Benson et al. (2003, 2004) reported PRR prevention in container-grown fraser fir seedlings in soilless substrate with dimethomorph, mixed results with fosetyl-aluminum and mefenoxam as a drench treatment, and poor results with hydrogen dioxide. Benson et al. (2006) found that mefenoxam as a soil spray and fosetyl-Al as a foliar spray were both able to delay PRR onset in fraser fir in a field setting. In North Carolina, mefenoxam is recommended if fungicide control of PRR in fraser fir is required (Sidebottom and Jones, 2004). The effectiveness of fungicides to prevent PRR in fraser fir incited by the species of *Phytophthora* common in Pennsylvania, *P. cactorum* and *P. drechsleri*, has not been studied. In Pennsylvania, recommended fungicides for PRR of firs include dimethomorph, hydrogen dioxide, mefenoxam, and propamocarb hydrochloride (Pennsylvania Department of Agriculture, 2009). The objectives of this study were to examine the efficacy of those four fungicides and fosetyl-Al in prevention of PRR incited by *P. cactorum* and *P. drechsleri* in fraser fir seedlings, as well as to test for differences between soil spray and drench treatments of mefenoxam.

Materials and methods

This study was conducted in Summer 2010 and Summer 2011 at the Russell E. Larson Agriculture Research Center at Rock Springs in Pennsylvania Furnace, PA (lat. 40°42'N, long.

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
16.3871	inch ³	cm ³	0.0610
28.3495	oz	g	0.0353
1	ppm	mg·L ⁻¹	1
0.001	ppm	mg·mL ⁻¹	1000
0.001	ppm	μL·mL ⁻¹	1000
1.1692	pt/acre	L·ha ⁻¹	0.8553
5.0932	pt/ft ²	L·m ⁻²	0.1963
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

77°56'W). Inoculation experiments were conducted both years in 112 outdoor raised planting boxes 33 inches by 12 inches by 7.25 inches (volume 2871 inch³). The boxes were filled with Hagerstown silt loam containing enough subsoil to classify as clay loam in 2010 and a mixture of topsoil classified as sandy loam in 2011. The factorial experiments contained three factors, fungicide (7 levels), *P. cactorum* (2 levels), and *P. drechsleri* (2 levels), for a combination of 28 treatments. Treatments were assigned on the box level, which was considered an experimental unit. A randomized complete block design was used with four blocks.

On 28 May 2010 and 4 May 2011, fraser fir 2-year-old seedlings were planted. Each box had 10 seedlings arranged in a row with 3-inch spacing between plants. Irrigation lines were installed with four spray stakes in each box. Watering was done at low pressure, resulting in drip irrigation; ≈ 2 cm of water was applied daily. Fertilization was provided every 4 weeks during the experiment with a 368 mg·L⁻¹ nitrogen (N) solution (21N-3.1P-5.8K; Scotts, Marysville, OH).

The fungicide treatments, including a control which received a plain water drench, were applied 10 June 2010 and 23 May 2011. Mefenoxam (Subdue Maxx; Syngenta Crop Protection, Greensboro, NC) was applied as a spray (2.5 pt/acre in 50 gal water) and a drench (1 fl oz/50 gal water, 2 pt/ft² solution). The soil spray treatment was watered in with 1.5 cm of water. Dimethomorph (Stature SC; BASF Corp., Research Triangle Park, NC) was applied as a drench (12 fl oz/50 gal water, 2 pt/ft² solution), and repeat applications were made on 14-d intervals. Hydrogen dioxide (ZeroTol; BioSafe, Glastonbury, CT) was applied weekly (1:100 rate, 2 pt/ft² solution). Propamocarb hydrochloride (Banol; Bayer Environmental Science, Research Triangle Park, NC) was applied as a drench (12.5 fl oz/50 gal water, 1.5 pt/ft² solution). Fosetyl-Al (Aliette; Bayer CropScience, Research Triangle Park, NC) was applied as a drench (25 oz/50 gal water, 4 pt/ft² solution).

Isolates of *P. cactorum* (Phytophthora Database ID: PD_00551) (Kang, 2012a) and *P. drechsleri* (Phytophthora

Database ID: PD_00640) (Kang, 2012b) were obtained from the Pennsylvania Department of Agriculture Plant Diagnostic Laboratory. The isolates were originally collected from diseased fraser fir seedling roots submitted to the laboratory. Inoculum of these isolates was cultured on long grain rice (*Oryza sativa*) using the methods of Holmes and Benson (1994). Long grain rice (25 g) was placed in an erlenmeyer flask (250 mL) with 18 mL of deionized water, stirred, capped with foil, and autoclaved 30 min. After sitting 24 h, the rice was stirred with a sterile rod, then autoclaved 30 min. After cooling, three 1-cm-diameter plugs of V8 agar containing *Phytophthora* cultures were placed in the flask. Each day for the next 14 d, the flasks were bumped against a firm, padded surface to ensure the rice grains remained separate and the contents were mixed. On 14 June 2010 and 24 May 2011, the *Phytophthora* inoculum was applied. Each *Phytophthora* species was a factor with levels of present and absent, the absent treatment was a control of plain autoclaved rice. Each plant received 0.5 g of rice from one level of each of the *P. cactorum* and the *P. drechsleri* factors sprinkled on the soil surface within a 1-inch radius of the stem. This resulted in four *Phytophthora* treatments, which are addressed by these titles: *Phytophthora* control (*P. cactorum* absent + *P. drechsleri* absent), PC (*P. cactorum* present + *P. drechsleri* absent), PD (*P. drechsleri* present + *P. cactorum* absent), and PC+PD (*P. cactorum* present + *P. drechsleri* present).

The experiment lasted 8 weeks in 2010 and 9 weeks in 2011. A weather station at the Russell E. Larson Agriculture Research Center provided air temperature and precipitation data throughout the experiments. Foliar disease ratings, adapted from the top ratings of Hinesley et al. (2000), were recorded for each seedling at the conclusion of the experiment. The ratings were as follows: 1 = healthy (no necrosis), 2 = mild symptoms (1% to 33% necrosis), 3 = moderate symptoms (34% to 67% necrosis), 4 = severe symptoms (68% to 99% necrosis), and 5 = dead (100% necrosis). The mean foliar disease rating of seedlings in each box was used for data analysis. Weekly plant mortality was recorded as a proportion of the

plants in each box that were dead. In 2011, at the conclusion of the experiment, all plants were harvested and oven dried at 150 °F for 10 d, then shoot and root dry weights were recorded.

Following the experiments, samples of dead roots were plated to detect the presence of *Phytophthora*. In preparation for plating, the roots were washed under running water, soaked in a 70% ethanol solution for 1 min, rinsed with deionized water, then blotted dry with paper towels. Sections of root 2–3 cm long were cut and placed on semiselective media containing corn meal agar, pimarin, ampicillin, rifampin, and pentachloronitrobenzene [PARP (Jeffers and Martin, 1986)]. Transfers were made to V8 agar. Morphological identification was carried out under a microscope using the key of Gallegly and Hong (2008).

A laboratory plating test was conducted to determine the sensitivity of the *P. cactorum* and *P. drechsleri* isolates used in this experiment to fosetyl-Al, mefenoxam, and propamocarb hydrochloride. Plugs (5 mm diameter) of mycelium were cut from the edge of cultures growing on V8 agar and placed on V8 agar plates containing the fungicides at label recommended rates (expressed as rate of fungicide per milliliter of medium: 3.7 mg·mL⁻¹ fosetyl-Al, 10 μ L·mL⁻¹ hydrogen dioxide, 0.1 μ L·mL⁻¹ mefenoxam, 9.8 μ L·mL⁻¹ propamocarb hydrochloride). Control plates contained no fungicide. Mycelium growth was measured on three axes on 24-h intervals.

Data from the foliar disease ratings at the conclusion of the experiments and the dry weights of shoots and roots at the conclusion of the 2011 experiment were analyzed with a Model III (mixed-model) analysis of variance (ANOVA) using PROC MIXED in SAS (version 9.3; SAS Institute, Cary, NC). Blocks were treated as random effects. Residual plots were created to confirm that the assumptions of ANOVA were satisfied. Residuals of the response variable were normally distributed, and the variances of the response variable were equal. Further testing with PROC GLIMMIX was used to perform multiple comparisons tests containing slice statements with an adjusted Tukey's Studentized range test. The foliar disease ratings at the conclusion of

the 2010 experiment were compared with those from 2011 with a Student's *t* test to determine if disease severity was different in the 2 years. Weekly mortality data were analyzed with a Model III (mixed-model) ANOVA containing a repeated measures statement using PROC GLIMMIX with an autoregressive covariance structure; multiple comparisons were conducted with an adjusted Tukey's Studentized range test. Mycelium growth data from the laboratory fungicide sensitivity experiment were analyzed with a Model I (fixed factor) ANOVA using PROC GLM in SAS, with multiple comparisons with a Tukey's Studentized range test. The significance level (α) used to reject null hypotheses for all statistical tests was set at 0.05.

Results and discussion

In 2010 and 2011, significant differences in Fraser fir seedling foliar disease ratings occurred between treatments (Table 1). A three-way interaction between fungicide, *P. cactorum*, and *P. drechsleri* precludes discussion of main effects (Table 1). The three-way interaction was caused by differences in fungicide efficacy, occurrence of species-specific efficacy with some fungicides, and, in 2010, differences in virulence of *Phytophthora* species.

Dimethomorph treatment resulted in seedlings with no significant differences in foliar disease ratings across all four *Phytophthora* treatments, including the *Phytophthora* control

(Table 2). All other fungicides had significantly higher ratings in one or more of the PC, PD, or PC + PD treatments than the *Phytophthora* control (Table 2). Fosetyl-Al or

Table 1. Mixed model analysis of variance for foliar disease ratings (1–5 scale)^a of Fraser fir seedlings exposed to *Phytophthora* and fungicide treatments at the conclusion of the 2010 and 2011 experiments.^b

Effect	df	F ^x	P
2010			
Fungicide ^w	6	30.72	<0.0001
<i>Phytophthora cactorum</i> ^v	1	155.57	<0.0001
<i>Phytophthora drechsleri</i> ^u	1	30.28	<0.0001
Fungicide × <i>P. cactorum</i>	6	8.82	<0.0001
Fungicide × <i>P. drechsleri</i>	6	1.53	0.1788
<i>P. cactorum</i> × <i>P. drechsleri</i>	1	9.53	0.0028
Fungicide × <i>P. cactorum</i> × <i>P. drechsleri</i>	6	2.27	0.0452
2011			
Fungicide	6	56.63	<0.0001
<i>P. cactorum</i>	1	145.96	<0.0001
<i>P. drechsleri</i>	1	50.28	<0.0001
Fungicide × <i>P. cactorum</i>	6	6.15	<0.0001
Fungicide × <i>P. drechsleri</i>	6	1.96	0.0807
<i>P. cactorum</i> × <i>P. drechsleri</i>	1	34.33	<0.0001
Fungicide × <i>P. cactorum</i> × <i>P. drechsleri</i>	6	3.76	0.0024

^aFoliar disease ratings scale: 1 = healthy (no necrosis), 2 = mild symptoms (1% to 33% necrosis), 3 = moderate symptoms (34% to 67% necrosis), 4 = severe symptoms (68% to 99% necrosis), 5 = dead (100% necrosis).

^bEach experiment contained four blocks, which were considered random effects.

^cType III F-statistic.

^wFungicide treatments: control (plain water drench), mefenoxam (soil spray), mefenoxam (drench), dimethomorph (drench), hydrogen dioxide (drench), propamocarb hydrochloride (drench), fosetyl-aluminum (drench).

^v*Phytophthora cactorum* treatments: present (0.5 g infested rice) and absent (0.5 g non-infested rice); 1 g = 0.0353 oz.

^u*Phytophthora drechsleri* treatments: present (0.5 g infested rice) and absent (0.5 g non-infested rice).

Table 2. Fraser fir seedling foliar disease rating least square (LS) means at the conclusion of the experiments with fungicide treatments and exposure to *Phytophthora* treatments.

Fungicide	<i>Phytophthora</i> treatment			
	None	<i>P. cactorum</i>	<i>P. drechsleri</i>	<i>P. cactorum</i> + <i>P. drechsleri</i>
Foliar disease rating (1–5 scale) ^a				
2010				
None	1.5 a ^y A ^x	4.6 c C	3.2 b B	4.6 d C
Dimethomorph	1.3 a A	1.2 a A	1.6 a A	1.4 a A
Fosetyl-aluminum	1.2 a A	3.1 b BC	2.3 ab AB	3.7 c C
Hydrogen dioxide	1.3 a A	4.5 c C	3.3 b B	4.8 cd C
Mefenoxam (soil spray)	1.3 a A	2.4 ab B	1.5 a AB	2.3 ab AB
Mefenoxam (drench)	1.6 a A	2.2 ab B	1.8 a A	3.1 bc B
Propamocarb hydrochloride	1.6 a A	4.5 c C	3.1 b B	4.5 cd C
2011				
None	2.5 ab A	5.0 d B	4.9 b B	5.0 c B
Dimethomorph	1.3 a A	1.1 a A	1.2 a A	1.3 a A
Fosetyl-aluminum	1.6 ab A	4.1 bc B	2.3 a A	4.4 bc B
Hydrogen dioxide	2.7 b A	5.0 d B	4.8 b B	5.0 c B
Mefenoxam (soil spray)	1.4 a A	3.6 b B	2.3 a A	4.2 bc B
Mefenoxam (drench)	1.7 ab A	4.1 b B	3.7 b B	3.7 b B
Propamocarb hydrochloride	2.3 ab A	4.8 bc B	4.5 b B	5.0 c B

^aFoliar disease ratings scale: 1 = healthy (no necrosis), 2 = mild symptoms (1% to 33% necrosis), 3 = moderate symptoms (34% to 67% necrosis), 4 = severe symptoms (68% to 99% necrosis), 5 = dead (100% necrosis).

^xFoliar disease rating LS means at the conclusion of the experiment, yearly LS means separation in columns with an adjusted Tukey's Studentized range test, values with the same lowercase letter in columns are not different at $P \leq 0.05$.

^yFoliar disease rating LS means at the conclusion of the experiment, yearly LS means separation in rows with an adjusted Tukey's Studentized range test, values with the same uppercase letter in columns are not different at $P \leq 0.05$.

mefenoxam soil spray treatment resulted in seedlings with the same foliar disease ratings in the *Phytophthora* control and PD treatments, which were lower than those in the PC and PC+PD treatments (Table 2). Within each *Phytophthora* treatment, the fungicide control, hydrogen dioxide, and propamocarb hydrochloride treatments all had seedling foliar disease ratings that were not significantly different from each other (Table 2). In 2010, those three fungicide treatments had lower seedling foliar disease ratings in the PD treatment than the PC or PC + PD treatments, while in 2011 the PC, PD, and PC + PD treatments were not significantly different (Table 2). This indicates that the foliar disease symptoms incited by *P. drechsleri* were more severe in 2011 than in 2010.

The most effective fungicide in preventing foliar disease symptoms incited by PRR in Fraser fir seedlings in 2010 was dimethomorph (Table 2). Drench treatment with mefenoxam was the same as soil spray treatment with mefenoxam, but it resulted in higher seedling foliar disease ratings than dimethomorph when exposed to PC + PD (Table 2). Fosetyl-Al reduced foliar disease incited by *P. cactorum* compared with the fungicide control, yet moderate disease was still present (Table 2). Propamocarb hydrochloride and hydrogen dioxide were not effective in preventing PRR symptoms regardless of the species present (Table 2). The most effective fungicide in preventing foliar disease symptoms in 2011 was dimethomorph (Table 2). Mefenoxam as a soil spray and fosetyl-Al were somewhat effective against *P. drechsleri*, with only mild to moderate foliar disease occurring. Mefenoxam as a soil spray and fosetyl-Al reduced foliar disease severity compared with the fungicide control with *P. cactorum*, but still allowed moderate to severe disease to occur (Table 2).

Mortality of seedlings exposed to *Phytophthora* had significant differences between fungicide treatments beginning in week 4 of the experiments, with the exception of the PC + PD treatment in 2011, which had significant differences in week 3 (Fig. 1) ($P \leq 0.05$). Seedlings in the *Phytophthora* control treatment did not have significant differences in seedling mortality between the fungicide treatments in

Fig. 1. Fraser fir mortality over time in seedlings treated with fungicides and exposed to *Phytophthora* treatments in 2010 and 2011. *Phytophthora* treatments were: no *Phytophthora* (control), *Phytophthora cactorum* (PC), *Phytophthora drechsleri* (PD), and *P. cactorum* plus *P. drechsleri* (PC + PD).

either year of the experiments (Fig. 1). Dimethomorph treatment resulted in the lowest mortality of seedlings exposed to *P. cactorum* (Fig. 1) ($P \leq 0.05$). In 2010, seedlings treated with mefenoxam and fosetyl-Al provided had substantially lower mortality rates when exposed to the PC treatment compared with the fungicide control, but that reduction was not as great in 2011 [percentage final mortality less than the fungicide control: mefenoxam-drench 2010 = 70%, 2011 = 22.5%; mefenoxam-spray 2010 = 57%, 2011 = 37.5%; fosetyl-Al 2010 = 42%, 2011 = 30% (Fig. 1)]. Mortality in seedlings exposed to the PD treatment was lowest with dimethomorph, mefenoxam, or fosetyl-Al treatment (Fig. 1) ($P \leq 0.05$). In 2011, the mefenoxam drench treatment was not as effective in reducing seedling mortality caused by *P. drechsleri* as it had been in 2010 (mortality percentage: 2010 = 10%, 2011 = 67.5%).

Based upon mortality data, the fungicide that was most effective in preventing PRR incited by *P. cactorum* was dimethomorph. The most effective fungicides in preventing PRR incited by *P. drechsleri* were dimethomorph, fosetyl-Al, and mefenoxam soil spray.

Dry shoot and root weight data from 2011 had significant differences based upon fungicide ($P < 0.0001$), *P. cactorum* ($P < 0.0001$), and *P. drechsleri* ($P < 0.005$) treatments, as well as an interaction between the *P. cactorum* and *P. drechsleri* treatments (Roots: $P = 0.0012$; Shoots:

$P = 0.0068$). Examination of simple effects revealed that when either *P. cactorum* or *P. drechsleri* was present, dry weight of seedling roots and shoots was lower than that of seedlings in the *Phytophthora* control ($P < 0.0001$). However, seedling dry weight was not significantly different in the PC, PD, and PC + PD treatments. This means that both species caused the same reduction in root and shoot mass, and the two species together did not produce a synergistic effect. Plants treated with dimethomorph and exposed to *Phytophthora* had greater root dry weights than those treated with propamocarb hydrochloride or the fungicide control (Table 3). Dimethomorph, fosetyl-Al, and mefenoxam as a soil spray all had no differences in Fraser fir root and shoot dry weights regardless of *Phytophthora* treatment. More differences in root and shoot weight might be expected if the experiment had been extended.

Both *Phytophthora* species were readily recovered from root samples of dead seedlings via plating. Root samples from dead seedlings from the PC + PD treatment yielded both species. No *Phytophthora* was isolated from roots of dead control seedlings, and only *Phytophthora* species applied as treatments were isolated from dead seedlings. In addition to root plating, control plants that died were visually examined for symptoms or signs of infection or infestation by organisms but none were found.

Table 3. Fraser fir seedling root and shoot dry weight least square (LS) means at the conclusion of the 2011 experiment with fungicide treatments and exposure to *Phytophthora* treatments.

Fungicide	<i>Phytophthora</i> treatment							
	None		<i>P. cactorum</i>		<i>P. drechsleri</i>		<i>P. cactorum</i> + <i>P. drechsleri</i>	
					Dry wt (g) ^z			
	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots
None	0.57 a ^y	1.55 a	0.33 b	0.75 b	0.30 b	1.03 ab	0.31 b	0.82 a
Dimethomorph	0.90 a	1.94 a	0.69 a	1.58 a	0.82 a	1.76 a	0.66 a	1.50 a
Fosetyl-aluminum	0.82 a	1.89 a	0.44 ab	1.17 ab	0.61 ab	1.52 ab	0.44 ab	1.28 a
Hydrogen dioxide	0.70 a	1.77 a	0.34 b	0.72 b	0.29 b	0.91 b	0.36 ab	0.78 a
Mefenoxam (soil spray)	0.73 a	1.54 a	0.55 ab	1.67 a	0.51 ab	1.20 ab	0.44 ab	1.43 a
Mefenoxam (drench)	0.70 a	1.71 a	0.36 b	1.17 ab	0.48 ab	1.46 ab	0.43 ab	1.27 a
Propamocarb hydrochloride	0.69 a	1.74 a	0.34 b	0.97 ab	0.40 b	1.12 ab	0.23 b	0.74 a

^z1 g = 0.0353 oz.^yDry weight LS means separation with an adjusted Tukey's Studentized range test, values with the same letter in columns are not different at $P \leq 0.05$.

The severity of foliar disease was greater in 2011 than it was in 2010 ($P = 0.0002$). This may have been due to environmental conditions. During the first 3 weeks of the 2010 experiment, there were 5 d with rainfall, totaling 0.5 inch of precipitation. In 2011, during the first 3 weeks of the experiment, there were 9 d with rainfall, totaling 2.4 inches of precipitation. This additional rainfall may have resulted in more opportunities for zoospore release, resulting in high levels of root disease. In 2011, there also appeared to be greater fluctuations in soil moisture levels than in 2010. The soil used in the 2011 experiment had less water holding capacity than that used in 2010 because of differences in texture (2010: 33% sand, 38.5% silt, 28.5% clay; 2011: 51.3% sand, 29.4% silt, 18.3% clay). After the first 3 weeks of the 2011 experiment, there was little precipitation. Maximum temperatures in 2011 were higher than in 2010. These higher maximum air temperatures coupled with the soil drainage characteristics made water stress more common in 2011 than in 2010. Seedlings with diseased root systems would be vulnerable to foliar damage during times of water stress because of their reduced ability to take up water.

In this study, mefenoxam and fosetyl-Al reduced the severity of PRR symptoms in fraser fir seedlings, yet were more effective against *P. drechsleri* than *P. cactorum*. Lack of sensitivity to mefenoxam in *P. cactorum* has been documented in isolates from infected strawberry (*Fragaria ×ananassa*) (Jeffers and Schnabel, 2004) and ginseng (*Panax quinquefolium*) plants (Hill and Hausbeck, 2005). Mefenoxam is

recommended for control of PRR in North Carolina (Sidebottom and Jones, 2004) and has been shown to have mixed effectiveness against *P. cinnamomi* (Benson et al., 2003, 2004, 2006). Fosetyl-Al also has been shown to have mixed effectiveness in preventing PRR symptoms caused by *P. cinnamomi* in fraser fir (Benson et al., 2003, 2004). In this study, mefenoxam and fosetyl-Al had species specific efficacy. Caution must be exercised in applying this result to field conditions because sensitivity of *P. cactorum* and *P. drechsleri* to mefenoxam and fosetyl-Al may vary across populations. *Phytophthora* isolates used in this experiment were very sensitive to mefenoxam and fosetyl-Al in laboratory testing (Table 4). This sensitivity suggests that the limitations in effectiveness of mefenoxam and fosetyl-Al in the inoculation experiments were due to lack of availability or quantity of the chemical in areas of infection, rather than resistance on the part of the *Phytophthora*.

Drench application of mefenoxam is more costly in labor and product than soil spray treatment. In this study, mefenoxam soil spray treatment was more effective than drench treatment in preventing seedling mortality and foliar disease incited by *P. drechsleri* in 2011. These findings, coupled with the economic advantages of using a soil spray treatment compared with a drench treatment, suggest that if mefenoxam is to be used a soil spray application is advisable.

Dimethomorph was the most effective fungicide for prevention of PRR incited by *P. cactorum* and *P. drechsleri* in fraser fir seedlings in this study. Seedlings treated with

dimethomorph and exposed to *Phytophthora* had the same foliar disease ratings and mortality rates as control seedlings not exposed to *Phytophthora*. Benson et al. (2003, 2004) also found dimethomorph to be effective in preventing PRR symptoms incited by *P. cinnamomi* in fraser fir. This suggests that dimethomorph is effective against at least three PRR-inciting *Phytophthora* species. While dimethomorph was very effective in preventing PRR incited by *P. cactorum* or *P. drechsleri*, the label-recommended 14-d interval of applications is not practical as a long-term solution. Dimethomorph is a systemic fungicide that is thought to inhibit germination of zoospores and disrupt hyphal cell wall development (Erwin and Ribeiro, 1996). The persistence and effectiveness of a single application of dimethomorph over time in fraser fir are not known. Benson et al. (2003, 2004) used the label recommended minimum rate applied on 30-d intervals with success in preventing PRR symptoms incited by *P. cinnamomi* in fraser fir. Determining the duration of dimethomorph efficacy is a critical part of assessing its economic feasibility in fraser fir seedling production.

Successfully managing PRR in fraser fir Christmas tree production requires an integrated control program. Critical components include avoiding exposure to *Phytophthora* inoculum through sanitation and reducing the activity of *Phytophthora* through ensuring proper soil drainage, which may be accomplished by proper site selection and site preparation before planting (Sidebottom and Jones, 2004). Chemical prevention of PRR is best used during the seedling or

Table 4. Mycelium growth of *Phytophthora* on V8 agar amended with fungicides^a and a non-amended control after 5 d.

Treatment	Mycelium growth (cm) ^y	
	<i>P. cactorum</i>	<i>P. drechsleri</i>
Control (no fungicide)	2.7 a ^x	3.5 a
Fosetyl-aluminum	0.0 c	0.0 c
Hydrogen dioxide	0.0 c	0.0 c
Mefenoxam	0.1 c	0.1 c
Propamocarb hydrochloride	1.9 b	2.3 b

^aFungicide rates expressed as rate of fungicide per milliliter of medium: 3.7 mg·mL⁻¹ fosetyl-aluminum, 10 µL·mL⁻¹ hydrogen dioxide, 0.1 µL·mL⁻¹ mefenoxam, 9.8 µL·mL⁻¹ propamocarb hydrochloride; 1 mg·mL⁻¹ = 1000 ppm, 1 µL·mL⁻¹ = 1000 ppm.

^yMycelium growth was measured on three axes for each sample, each treatment had six replicates; 1 cm = 0.3937 inch.

^xMeans within a column with the same letter are not different based on a Tukey's Studentized range test at $P \leq 0.05$.

transplant bed stages of production as an occasional supplement and should not be viewed as a primary control measure. Use of fungicides to prevent PRR in the field stage of Fraser fir Christmas tree production is not common (Benson et al., 2006). Caution should be taken in extrapolating the results of fungicide tests with seedlings to field conditions.

Literature cited

Benson, D.M. and L.F. Grand. 2000. Incidence of phytophthora root rot of Fraser fir in North Carolina and sensitivity of isolates to *Phytophthora cinnamomi* to metalaxyl. Plant Dis. 84(6): 661–664.

Benson, D.M., L.F. Grand, and E.G. Suggs. 1976. Root rot of Fraser fir caused by *Phytophthora drechsleri*. Plant Dis. Rptr. 60:238–240.

Benson, D.M., K.C. Parker, and J. Sidebottom. 2003. Efficacy of Biophos, Vital, Stature-DM, Alette, ZeroTol, and Subdue Maxx for control of phytophthora root rot of Fraser fir, 2002. Fungicide Nematicide Tests 58:OT003.

Benson, D.M., K.C. Parker, and J. Sidebottom. 2004. Efficacy of Biophos, Vital, Stature-DM, Alette, ZeroTol, and Subdue Maxx for control of phytophthora root rot of Fraser fir, 2003. Fungicide Nematicide Tests 59:OT023.

Benson, D.M., J.R. Sidebottom, and J. Moody. 2006. Control of phytophthora root rot in field plantings of Fraser fir with fosetyl-al and mefenoxam. Plant Health Prog., doi: 10.1094/PHP-2006-0331-01-RS.

Bruck, R.I. and C.M. Kenerley. 1981. Effect of metalaxyl on phytophthora root rot of Fraser fir. Phytopathology 71(8): 864. (abstr.).

Bruck, R.I. and C.M. Kenerley. 1983. Effects of metalaxyl on *Phytophthora cinnamomi* root rot of *Abies fraseri*. Plant Dis. 67(6):688–690.

Erwin, D.C. and O.K. Ribeiro. 1996. Phytophthora diseases worldwide. APS Press, St. Paul, MN.

Gallegly, M.E. and C. Hong. 2008. Phytophthora: Identifying species by morphology and DNA fingerprints. APS Press, St. Paul, MN.

Hill, S.N. and M.K. Hausbeck. 2005. Characterization of *Phytophthora cactorum* isolated from American ginseng. Phytopathology 95(6S):S163. (abstr.).

Hinesley, L.E., K.C. Parker, and D.M. Benson. 2000. Evaluation of seedlings of Fraser, momi, and Siberian fir for resistance to *Phytophthora cinnamomi*. HortScience 35(1):87–88.

Ho, H.H. and S.C. Jong. 1991. Species concepts of *Phytophthora cryptogea* and *P. drechsleri*. Mycotaxon 40:35–39.

Holmes, K.A. and D.M. Benson. 1994. Evaluation of *Phytophthora parasitica* var. *nicotianae* for biocontrol of *Phytophthora parasitica* on *Catharanthus roseus*. Plant Dis. 78(2):193–199.

Jeffers, S.N. and S.B. Martin. 1986. Comparison of two media selective for *Phytophthora* and *Pythium* species. Plant Dis. 70(11):1038–1043.

Jeffers, S.N. and G. Schnabel. 2004. First report of resistance to mefenoxam in *Phytophthora cactorum* in the United States and elsewhere. Plant Dis. 88(5): 576.

Kang, S. 2012a. Phytophthora database: Isolate browser: PD_00551. 31 Mar. 2012. <<http://www.phytophthoradb.org/isolate.php?a=dv&id=551&p=17&cl=30&sv=&sf=>>>.

Kang, S. 2012b. Phytophthora database: Isolate browser: PD_00640. 31 Mar. 2012. <<http://www.phytophthoradb.org/isolate.php?a=dv&id=640&p=3&cl=30&sv=&sf=>>>.

Kuhlman, E.G. and F.F. Hendrix, Jr. 1963. Phytophthora root rot of Fraser fir. Plant Dis. Rptr. 47:552–553.

Mitcham-Butler, E.J., L.E. Hinesley, and D.M. Pharr. 1988. Effect of harvest date, storage temperature, and moisture status on postharvest needle retention of Fraser fir. J. Environ. Hort. 6(1):1–4.

Mostowfizadeh-Ghahamfarsa, R., F. Panabieres, Z. Banihashemi, and D.E.L. Cooke. 2010. Phylogenetic relationship of *Phytophthora cryptogea* Pethybr. & Laff and *P. drechsleri* Tucker. Fungal Biol. 114(4):325–339.

Owen, J.H. 2005. Selecting sites for Fraser fir production. North Carolina State Univ. Coop. Ext. Christmas Tree Notes CTN-036.

Pennsylvania Department of Agriculture. 2009. Fungicides for common PA diseases in conifer nurseries. Pennsylvania Dept. Agr., Harrisburg, PA.

Quesada-Ocampo, L.M., D.W. Fulbright, and M.K. Hausbeck. 2009. Susceptibility of Fraser fir to *Phytophthora capsici*. Plant Dis. 93(2):135–141.

Shew, H.D. and D.M. Benson. 1981. Fraser fir root rot induced by *Phytophthora citricola*. Plant Dis. 65(8):688–689.

Sidebottom, J. and R. Jones. 2004. Management of phytophthora root rot in Fraser fir Christmas trees. North Carolina State Univ. Coop. Ext. Christmas Tree Notes CTN-022.

Tompkins, D. 2000. Looking forward - Views from the Northeast. Amer. Christmas Tree J. 44(1):12–15.

U.S. Department of Agriculture. 2009. Census of horticultural specialties. Vol. 3. Part 3. U.S. Dept. Agr. AC-07SS-3.

Williams, R. 2002. Evaluation of the competitive position of the Fraser fir Christmas tree. 1 Apr. 2012. <<http://www.ncagr.gov/stats/crops/ChristmasTreeBuyers2001.pdf>>.