Fungicidal Suppression of Swiss Needle Cast and Pathogen Reinvasion in a 20-Year-Old Douglas-Fir Stand in Oregon

Jeffrey K. Stone, Paul W. Reeser, and Alan Kanaskie

ABSTRACT

Aerial applications of chorothalonil fungicide were carried out annually over 5 consecutive years, 1996–2000, on three sets of paired, 2-ha units in a Douglas-fir plantation affected by Swiss needle cast in the Oregon Coast Range. The effect of treatment on disease control was evaluated annually from 2001 to 2004. One- and 2-year-old foliage in the fungicide-treated units had fewer fruiting bodies of the pathogen *Phaeocryptopus gaeumannii* compared with the unsprayed units for foliage sampled in 2001. Total needle retention was also greater in the fungicide-treated units after five consecutive annual fungicide applications. Reduced *P. gaeumannii* infection in the fungicide-treated units persisted for foliage produced in 2001, which did not receive direct fungicide treatment. Reduced infection levels in the 2001 foliage cohort in the treated units was presumed to be due to the effect of disease control on inoculum production. At 4 years following the final treatment application, infection levels averaged over four foliage cohorts (2000–2003) remained significantly smaller for the fungicide-treated units. Trees in fungicide-treated units retained 10–50% of the 2000 needle cohort (4-year-old needles) and 25–60% of the 2001 cohort in May 2004. However, there was no detectable effect of treatment on infection for 2002 foliage sampled in 2003 or for 2003 foliage sampled in 2004 (1-year-old needles), suggesting that the duration of disease control was relatively brief.

Keywords: *Phaeocryptopus gaeumannii*, chlorothalonil, foliage disease

Swiss needle cast disease is a foliage blight of Douglas-fir caused by the ascomycete fungus *Phaeocryptopus gaeumannii*. Extensive colonization of needles by the pathogen causes impaired CO_2 assimilation, resulting in premature needle loss (Manter et al. 2000, 2003). Severe disease can cause all but the current year's foliage cohort to be lost, compared with normal Douglas-fir needle retention of approximately 4 years (Hansen et al. 2000). Reduced foliage retention due to Swiss needle cast can result in volume growth reductions of between 30% and 53% for the most heavily diseased stands relative to stands with normal needle retention (Maguire et al. 2002, 2004).

Although the pathogen is widely distributed on Douglas-fir in western Oregon and Washington, extensive and severe Swiss needle cast disease historically has been uncommon in forest plantations in the Pacific Northwest. Boyce (1940) considered the fungus widespread but harmless to Douglas-fir throughout its native range, in contrast to the situation in Europe and eastern North America where Douglas-fir was grown as an exotic species, and defoliation due to Swiss needle cast was severe. Sporadic outbreaks of Swiss needle cast in forest plantations in Oregon and Washington have been reported since the 1970s (Hansen et al. 2000, Russell 1981), and an exceptionally severe and persistent outbreak has affected plantations in the Coast Range of western Oregon since about 1990 (Hansen et al. 2000). The area affected by severe Swiss needle cast encompasses the entire length of the western flank of the Oregon Coast Range, extending some 30 km inland, an area of approximately 1.2 million ha. Forest plantations having moderate to severe symptoms increased from approximately 53,000 ha in 1996 to 157,000 ha in 2002, as determined by aerial surveys conducted annually since 1996 by the Oregon Department of Forestry. Since 2002, the area of symptomatic plantations has diminished to approximately 73,000 ha (Kanaskie et al. 2004). Annual losses of 40 million board feet due to Swiss needle cast have been estimated for the entire affected area (Maguire et al. 2002, 2004).

Management options for controlling Swiss needle cast in forest plantations are very limited at present, and the potential for control of Swiss needle cast by fungicides has not received much attention in the United States. The fungicide chlorothalonil is recommended for control of the disease in Douglas-fir Christmas tree plantations (Skilling 1981, Hadfield and Douglas 1982, Chastagner and Byther 1983, Pscheidt and Ocamb 2005). Annual applications of chlorothalonil are recommended beginning 3 years prior to planned harvest for marketable Christmas trees (Chastagner and Byther 1983). Field studies have shown that chlorothalonil fungicide is also effective in controlling Swiss needle cast in young forest plantations (Chastagner and Stone 2001), but disease control in larger trees presents additional challenges. Because of the longer duration of disease control needed for Douglas-fir forest rotations, aerial fungicide sprays have not been considered an economically effective option for control of Swiss needle cast in operational forestry.

Annual applications of fungicide throughout a normal forest rotation for Swiss needle cast control would probably be prohibitively

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expensive. However, some aspects of *P. gaeumannii* biology suggest that continuous annual spray applications throughout a rotation might not be necessary for disease control. The fungus has long been present in the Pacific Northwest, where it is considered native, and Douglas-fir trees normally can sustain a limited amount of infection without adverse effects. Complete suppression of the pathogen, therefore, should not be required to achieve disease control. Satisfactory disease control might be achieved by reducing infection to endemic levels. Furthermore, needles are susceptible to infection almost exclusively only during their first growing season, and most infection occurs during periods of intermittent rainfall from late May through June (Chastagner and Byther 1983, Michaels and Chastagner 1984, Stone et al. 2007). Needles more than 1 year old are only negligibly susceptible to new infection by ascospores (Hood and Kershaw 1975, Stone et al. 2007). Therefore, needles only require protection for a few weeks during the peak period of ascospore release, late May through mid-June of the first growing season, to keep them disease-free for their normal lifetime of 4–5 years. Because diseased trees typically lose all but 1- and 2-year-old needles, effective spray applications for 2 or 3 consecutive years might eliminate, or significantly reduce, levels of infection and inoculum production in forest stands, reducing the need for treatment in subsequent years.

Previous attempts to control Swiss needle cast in forest plantations by applications of fungicides met with mixed results. Aerial application of a copper fungicide was ineffective in reducing *P. gaeumannii* infections in a 19-year-old forest stand of Douglas-fir in New Zealand. However, hand spraying the same material at the same concentration reduced the proportion of infected needles to below 42%, compared with 100% in unsprayed control (Hood and van der Pas 1979). Control of Swiss needle cast in forest stands with chlorothalonil has not previously been attempted.

This study was undertaken to evaluate the efficacy of annual aerial fungicide applications in reducing infection levels of *P. gaeumannii* in forest stands and to determine the duration of residual disease control in the presence of continued exposure to natural inoculum. This study was carried out in cooperation with the Oregon Department of Forestry, which treated study sites with annual aerial applications of chlorothalonil fungicide between 1996 and 2000. Foliage produced in the spring of 2001 was the first cohort of untreated foliage after 5 consecutive years of fungicide application. Amounts of infection in the untreated and treated units were monitored for the 2001 and subsequent needle cohorts to assess the duration of disease control after the final treatment application. Infection levels of *P. gaeumannii* in foliage and foliage retention were measured for 1- and 2-year-old needles, and the effect of fungicide treatment was assessed annually from 2001 to 2004.

Materials and Methods

Aerial sprays were applied to a study site established by the Oregon Department of Forestry near Beaver, OR (45°17′24″N, 123°48′36″W). The study site was a Douglas-fir plantation established in 1980 located on the western slope of the Coast Range 16 km inland from the Pacific Ocean at an elevation of approximately 180 m. The site was characterized as having severe Swiss needle cast disease in 1995. The study was designed as a complete randomized block experiment with three 4-ha blocks, each of which was divided into two 2-ha experimental units. One unit of each block was treated with fungicide (T1, T2, and T3), the second unit of each pair was not sprayed (C1, C2, and C3). Bravo WeatherStik 720 (Syngenta Crop Protection, Greensboro, NC) fungicide was applied at a rate of 6.4 L/ha in 280 L of H_2O by helicopter aerial spray in two perpendicular directions to ensure complete coverage. Two fungicide applications were made each year for 5 consecutive years, 1996–2000. The first applications were made in late May of each year shortly after bud break, when new shoots on approximately 40% of the trees averaged 1–5 cm. The second application was made approximately 14 days after the first application, when buds of more than 90% of trees had opened.

Two transects were established in each of six 2-ha experimental units. Transects were oriented perpendicular to each other and crossed the units from edge to edge from approximately the midpoint of each side. Sampling points were located at approximately 30-m intervals along each transect, starting at approximately 15 m in from the edge. Each transect had six sample points except in unit T3, a long narrow unit, which had eight sample points in one transect and four in the other. Foliage was sampled from two trees at each sample point. A pole pruner was used to cut two secondary lateral branches from the fifth whorl from the top.

Needle retention on the sampled branches was assessed in the field, and then foliage samples were placed in bags and returned to Oregon State University for infection assessments. Samples were collected from units C1, C2, T1, and T2 in May 2001 and May 2002 and from all six units in May 2003 and May 2004. Needle retention was visually estimated and rated for each annual needle cohort (age class) on a scale of 1–9, where 9 = 90–100% needles remaining attached, for the previous four annual cohorts, starting with the current-year cohort. Retention ratings for each internode of the four cohorts were summed to obtain a composite retention index (RI) for each branch (e.g., 90–100% needle retention for all four cohorts would be RI = 36).

Numbers of ascocarps (pseudothecia) on needles were used for assessment of *P. gaeumannii* infection. Needles were removed from internodes and separated by age class, placed in envelopes and stored frozen (−20° C). A sample of 50 needles/age class/branch/tree was randomly drawn for pseudothecia counts. Needles were affixed with the abaxial side up to index cards with double-sided adhesive tape and examined under a dissecting microscope to determine the proportion of needles bearing pseudothecia (incidence of infection). The first 10 needles on each card with pseudothecia present were then used to determine the proportion of stomata occupied by pseudothecia (severity). The needles were examined under a dissecting microscope fitted with a counting grid, and the proportion of stomata occupied by pseudothecia in three segments (base, middle, and tip) of each of the 10 needles was determined. Infection index (I), the product of incidence times severity, was used as a response variable for comparisons of treatments. Statistical analyses were performed with SAS for Windows, version 8 (SAS Institute, Cary, NC), and Statgraphics (Manuguistics Inc., Rockville, MD).

Results

All four foliage cohorts sampled in May 2001 (1997–2000 cohorts) had received direct fungicide treatment soon after bud break. For foliage sampled in May 2001, needle retention was significantly greater in units that had been treated with fungicide for 5 years ($P < 0.05$; Table 1). The average RI for treated plots, 27.3, represents approximately 75% of foliage in age classes 1–4 retained, compared with approximately 40% for the unsprayed control stands (RI = 14.2). Nearly all 1-year-old (2000 cohort) needles were retained in both treatments. Retention of the 2-year-old (1999 cohort) needles

Table 1. Comparison of infection index (I) for three Douglas-fir needle age classes from annual samples, 2001–2004.[a]

Sample Year	1-year-old	2-year-old	3-year-old
2001	2000	1999	1998
Check	17.5	30.0	38.5
Fungicide	3.5*	14.0*	20.0*
2002	2001	2000	1999
Check	15.0	38.0	48.5
Fungicide	9.0*	14.5*	23.5*
2003	2002	2001	2000
Check	20.0	46.3	41.0
Fungicide	17.0	36.3	32.7*
2004	2003	2002	2001
Check	10.3	26.3	21.7
Fungicide	12.3	26.0	24.0

[a] Fungicide treatment was annually applied from 1996 to 2000. Significant difference between means in the same column at $P < 0.05$ is indicated by an asterisk (*).

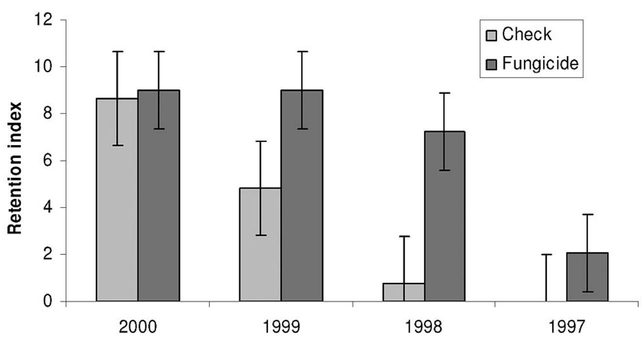

Figure 1. Average foliage retention ratings by needle cohort for fungicide-treated versus untreated units after 5 consecutive years of fungicide applications. Bars denote SE.

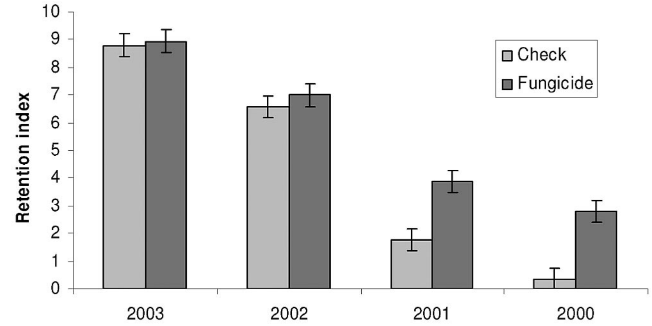

Figure 2. Average foliage retention ratings by needle cohort for fungicide-treated versus untreated units sampled at 4 years after the final fungicide application (2004). Bars denote SE.

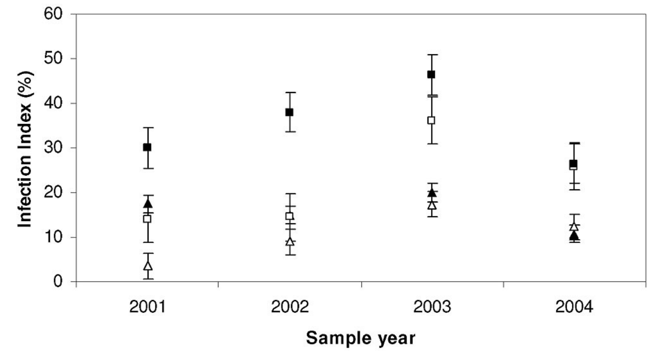

Figure 3. Change in infection index over 4 years following cessation of fungicide application. △, 1-year-old needles, fungicide-treated; ▲, 1-year-old needles, check; □, 2-year-old needles, fungicide-treated; ■, 2-year-old needles, check. Bars denote SE.

also was near 100% in the fungicide-treated units, but only approximately 50% of this cohort was retained in the unsprayed units. Of the 3-year-old 1998 needle cohort, 70–80% was retained in the treated units, compared with less than 10% for the control units. A small proportion of 4-year-old 1997 needles remained on the fungicide-treated trees, but this cohort was completely absent from the untreated units (Figure 1).

For the foliage sampled in 2004, only the 4-year-old (2000) needle cohort had received direct fungicide treatment. There was no detectable difference between the treated and untreated units in retention of 1-year-old needles. Retention of 1-year-old (2003 cohort) needles was near 100% for both groups. Retention of the 3- and 4-year-old needles in fungicide-treated units was greater than in the unsprayed units (Figure 2).

Incidence of infection, the proportion of needles bearing at least one fruiting body, measured in May 2001 was near 100% for fungicide-sprayed as well as unsprayed plots for all needle cohorts (data not shown), indicating that virtually all needles had the pathogen present, regardless of treatment. However, abundance of the pathogen was reduced by the fungicide treatment. The infection index (I) was significantly smaller for all needle cohorts measured in May 2001 (Table 1). Because there was no difference in proportion of infected needles between treatments, differences in infection index between treatments reflects differences in abundance of fruiting bodies on needles. Age class 2000 foliage from fungicide-treated plots had one-half to one-third the level of infection (infection index) present in the unsprayed control at 2 years following emergence. Infection index for 2001 foliage (sampled in May 2002) was also significantly greater for the unsprayed controls than in the fungicide-treated plots, although differences were not as great (Table 1).

Differences between treatments persisted through the first year that aerial fungicide sprays were not applied to the treatment plots. Infection index remained significantly smaller for all needle cohorts in fungicide-treated units sampled in 2002. However, infection index in fungicide-treated units was significantly smaller only for the 3-year-old (2000) needle cohort sampled in 2003. Infection index for 1- and 2-year-old needles from treated units were not significantly different from checks. There were no significant differences in infection index for any needle cohort from fungicide-treated and unsprayed units for the 2004 sample (Table 1). Infection levels in needle cohorts produced following cessation of spray applications gradually converged, and by 4 years after the final fungicide application, infection levels in 1- and 2-year-old needles were equivalent in the fungicide-treated and unsprayed units (Figure 3).

Discussion

Fungicide applications for 5 consecutive years resulted in concurrent reduction of *P. gaeumannii* infection and significantly greater foliage retention in the fungicide-treated compared with the unsprayed units. Needle retention in current-year needles was not different between sprayed and unsprayed units, as expected. Needles are normally retained for at least 1 year regardless of disease severity (Hansen et al. 2000). However, increased retention of the 2- and 3-year-old needles resulted in approximately 1 additional year of foliage in the sprayed versus unsprayed units in 2001, reflecting the effect of fungicide treatment on disease control. A separate analysis of wood characteristics from these units showed that untreated control trees also had less wood moisture content, decreased ring width, and increased latewood proportion compared with fungicide-treated trees, characteristics that have been attributed to reduced vigor and defoliation due to disease (Johnson et al. 2001). Because fungicide treatment resulted in reduction of *P. gaeumannii* and concomitant increases in foliage retention and volume growth, these results reinforce the conclusion that *P. gaeumannii* is the primary agent responsible for the observed decline of Douglas-fir in Oregon and Washington, rather than nutritional imbalances or abiotic stress.

The last needle cohort to receive direct fungicide treatment was produced in the spring of 2000. Healthy coastal-form Douglas-fir typically retain needles up to 5 years; therefore, after 5 consecutive years of treatment, it was assumed that all attached foliage cohorts in the sprayed units had received direct fungicide treatment. Because all foliage cohorts sampled in May 2001 had received at least one annual fungicide treatment, this sample should represent the greatest disease control.

Foliage from fungicide-treated units had significantly reduced levels of *P. gaeumannii* compared with unsprayed controls in 2001 foliage measured in May 2002. Since this foliage had not been sprayed with a protectant fungicide, reduced infection levels in this needle cohort probably reflect reduced inoculum levels resulting from multiple-year treatment in the fungicide-sprayed units. However, it appears that the residual effect of disease control on differences in infection levels between fungicide-treated and unsprayed plots after multiyear treatment was short-lived relative to the duration of control needed for forestry rotations. In the first year following suspension of annual spray applications, infection levels in 1-year-old foliage already were beginning to converge in this first cohort of foliage that did not directly receive fungicide. In subsequent 2003 and 2004 samples, infection levels in the fungicide-treated units continued to increase, converging toward levels of the untreated units. Infection levels in the 1-year-old 2002 foliage from the two treatments were not statistically different. This suggests that even after five consecutive annual aerial fungicide applications, sufficient residual infection remained in the crowns of treated trees to enable infection levels to rapidly return to pretreatment levels only 2 years after the cessation of fungicide treatment.

The rapid buildup of disease from a small initial population is consistent with the predictions of the disease prediction model of Manter et al. (2005). In this model, the maximum pathogen population is limited by winter temperature. A model simulation of pathogen population growth from a very small initial starting population resulted in recovery of the pathogen population to equilibrium level in only 2 years for 1-year-old foliage (Manter et al. 2005).

Chlorothalonil has previously been effective in controlling Swiss needle cast in Christmas trees (Chastagner and Byther 1983) and forest plantations (Chastagner and Stone 2001). The WeatherStik formulation of chlorothalonil (Daconil) provided control superior to that of other formulations (Chastagner and Stone 2001). Even though chlorothalonil fungicide significantly reduced *P. gaeumannii* levels in this study and others, complete elimination of the pathogen from the stands was not expected. Detectable residual levels of infection typically remain even where good disease control has been achieved (Chastagner and Byther 1983, Chastagner and Stone 2001). The amount of residual infection following a course of treatment is probably the most important factor affecting long-term disease control. The amount of residual infection will be determined by the efficacy of the treatment, initial disease severity, coverage, and timing. In this study, the amount of residual infection remaining after 5 years of treatment was relatively high.

Although significant differences in infection levels were detected between treatments, our data suggest that the aerial fungicide spray treatment was only minimally effective in controlling *P. gaeumannii* in this forest stand. Incidence of infection in fungicide-treated age class 2000 needles, measured in May 2002, was nearly 100%, not significantly different from the unsprayed control, even though infection index (the product of incidence times severity) was significantly different (Table 1). This shows that even though the fungicide treatment reduced the relative amounts of infection in these needles, there was still sufficient residual inoculum to effectively saturate foliage. Numbers of fungal fruiting bodies on foliage from the sprayed units was one-third to one-half that of the untreated control and accounted for the observed differences between treatments. The initial level of disease at this site was characterized as severe, and the extraordinarily high disease pressure may have hampered disease control. Field studies with elemental sulfur fungicides on sites with less severe disease have resulted in greater reductions of *P. gaeumannii* infection, even though elemental sulfur has not been as effective as Bravo (Daconil) when these materials have been compared (Stone et al. 2004).

Aerial application of a copper fungicide was ineffective in reducing *P. gaeumannii* infections in a 19-year-old forest stand of Douglas-fir in New Zealand. However, hand spraying the same material at the same concentration reduced incidence of infection to below 42% compared with 100% in unsprayed control (Hood and van der Pas 1979). The success of the hand spray application was attributed to superior foliage coverage and greater amounts of material applied. Hand spray applications were applied to runoff by a person climbing within the tree crowns. This underscores the difficulty of achieving sufficient aerial application rates in forest tree stands compared with Christmas trees, where Swiss needle cast is routinely controlled by protectant fungicides. The relatively high levels of residual infection present in the fungicide-treated units in our study suggest that coverage may have been inadequate. Fungicide application volumes for forestry will require adjustments based on crown volume and foliage area rather than a standard rate per acre. It is also possible that because of the severity of disease at this site, fungicide applications were ineffective. Aerially applied fungicides might prove more effective in controlling Swiss needle cast at sites with more moderate levels of disease.

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